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Drainage reversal toward cliffs induced by lateral lithologic differences

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ABSTRACT

Drainage reversals, an end-member case of drainage reorganization, often occur toward cliffs. Reversals are commonly identified by the presence of barbed tributaries, with a junction angle >90°, that preserve the antecedent drainage geometry. The processes that form reversed drainages are largely unknown. Particularly, barbed tributaries cannot form through a spatially uniform migration of the cliff and drainage divide, which would be expected to erase the antecedent drainage pattern, and tectonic tilting toward the cliff that could reverse the flow direction is inconsistent with geodynamic models of large-scale escarpment, where many reversals are documented. Here, we propose a new mechanism for drainage reversal, where the slope imbalance across a cliff, together with the high erodibility of sediments that fill cliff-truncated valleys, result in faster divide migration along valleys compared to interfluves. We demonstrate this mechanism along channels that drain toward the escarpment of the Arava Valley in Israel. Reversal is established by observations of barbed tributaries and opposite-grading terraces. We show that drainage reversal occurs when erodible valley fill exists, and that the reversal extent correlates with the thickness of this fill, in agreement with the predictions of the proposed mechanism. This new reversal mechanism demonstrates that valley fill could play an acute role in fluvial reorganization processes, and that reversals could occur independently of tectonic tilting.

INTRODUCTION

Drainage reversal is a mode of fluvial reorganization that occurs when a channel that previously graded in in one direction reversed its gradient to the opposite direction, while exploiting its antecedent valley. Reversed drainages are recognized by an in-valley wind gap at their headwaters and by barbed tributaries, where the tributary junction angle, >90° (Haworth and Ollier, 1992; Prince et al., 2010), preserves the antecedent geometry and topology (Fig. 1). Reversed drainages have been documented in various tectonic and topographic settings (e.g., Davis, 1889; Clark et al., 2004) and are particularly common where extreme slope asymmetry occurs across a water divide.

Slope asymmetry is inherent along shoulder-type topographic escapements, where a major water divide coincides with the escarpment's cliff (Tucker and Slingerland, 1994; Matmon et al., 2002; Petit et al., 2007; Godard et al., 2019) (Fig. 1). Such escarpments occur over a wide range of scales, from great escarpments (10^2–10^3 km) that form in association with rifted passive margins, to erosional escarpments (10^0–10^2 km). The latter form where deeply incised basins are juxtaposed against low-relief, high-elevation terrain (Strahler, 1952) due to, for example, lateral lithologic differences (Gallen, 2018) or differences in base level (Struth et al., 2019). Extreme slope asymmetry across a divide can also stem from river capture that redirects the drainage area to a lower base level (Bishop, 1995). The capture forms a cliff that coincides with a local divide that separates the new local base level from the truncated antecedent channel, downstream of the capture (Fig. 1).

In both settings, namely, topographic escarpments and the cliff downstream of a capture point, reversals, with and without barbed tributaries, have been documented to occur toward the cliff, such that the divide that used to coincide with the cliff is pushed inland along the antecedent valley (Figs. DR1–DR4 in the GSA Data Repository[1]) (e.g., Haworth and Ollier, 1992; Prince et al., 2010, 2011). Such reversals pose a mechanistic problem in being inconsistent with a model of uniform cliff retreat, where the divide and the cliff migrate uniformly (Bishop, 1995) and replace the antecedent highland pattern with a rejuvenated network that initiates at the cliff and flows toward the lowland (Fig. DR5).

Alternatively, tectonic tilt that is opposite to the gradient of the main channel is commonly invoked to explain drainage reversals (Bishop, 1995) (Fig. DR5). Independent evidence for such tectonic tilt, however, is rare, and instead the occurrence of barbed tributaries is sometimes cited as evidence for the tectonic tilt (e.g., Clark et al., 2004). In great, shoulder-type escarpments, tectonic tilting toward the escarpment cliff is particularly problematic. Isostatic adjustment to erosional unloading (Turcotte and Schubert, 2014) and the flexural response due to deep-rooted normal faults that accompany some escarpments (e.g., King and Ellis, 1990) produce an opposite tilt toward the highlands and away from the cliff (Gilchrist and Summerfield, 1990), in contrast to the reversal direction cited here (Fig. DR5).

Reconciling these apparently contradicting observations is critical for explaining processes of drainage reorganization and assessing cliff evolution. Here we propose a new mechanism for drainage reversal toward cliffs that is based on the largely overlooked difference in erodibility between valley-filling sediments and bedrock interfluves (areas of higher ground that separate two neighboring river valleys).

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[1]GSA Data Repository item 2019332, supplementary table, field area description, methods, and supplementary figures, is available online at http://www.geosociety.org/datarepository/2019/, or on request from editing@geosociety.org.

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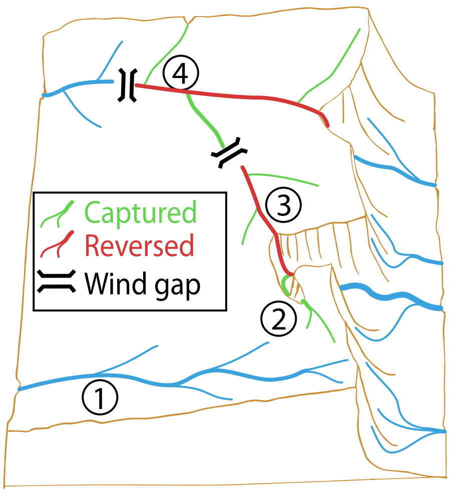

Figure 1. Cartoon showing different drainage settings near a cliff. In basin 1, no reversal is present, and the drainage divide coincides with the cliff. Segments 2 and 3 were a tributary of basin 4 until segment 2 was captured to flow across the cliff, and subsequently segment 3 was reversed toward the capturing basin. Note that reversal is not an integral part of capture, but a separate process that may follow it. The main trunk of basin 4 was reversed and its tributaries were captured, forming a barbed morphology. Reversed segments are bounded by wind gaps at their headwaters.

PREFERENTIAL DIVIDE MIGRATION AS A MECHANISM FOR FLOW REVERSAL

During retreat of a shoulder-type escarpment, preexisting highland drainages that flow away from the escarpment are truncated by the retreating escarpment cliff, and topographic saddles form where the cliff truncates these antecedent valleys. Similar saddles occur where a cliff truncates an antecedent channel following a capture. Commonly, the bed of these truncated channels is covered with poorly consolidated, erodible sediments (Fig. 2A; Fig. DR6A). These could be fluvial sediments of the antecedent channel that had a larger drainage area prior to the truncation, and/or colluvial deposits from adjacent hillslopes. In the mechanism we propose, the presence of an erodible layer that covers the channel bed promotes differential divide migration, with faster rates along the antecedent valley with respect to the interfluves, which are underlain by less-erodible bedrock. Divide migration within the valley occurs by hillslope processes due to slope asymmetry across the divide (Gilbert, 1877; Mudd and Furbish, 2005). On the side that faces the cliff, the steep slope promotes rapid transport of the erodible fill toward and down the cliff (e.g., BenDror and Goren, 2018). On the opposite side, the shallow slope of the antecedent valley hinders sediment transport. The different transport rates across the divide (West et al., 2013) induce divide migration along the valley and away from the cliff. As the divide migrates within the erodible fill, it increases the area that drains toward the cliff (Fig. 2B), leading to the formation of a reversed channel (i.e., a channel whose gradient was reversed) between the receding divide and the cliff. This reversed segment incises into the erodible fill and flows toward the cliff, where it forms a waterfall.

Divide migration continues as long as the average slope between the divide and the cliff is steeper than the slope of the antecedent valley on the opposite side of the divide. The higher slope (for the same drainage area) of the reversed channel results in increased erosion rate and lowering of the local base level for the cliff-facing hillslope, which maintains the asymmetry in hillslope gradient across the divide. When the receding divide traverses a tributary confluence, the tributary joins the reversed segment and forms a barbed tributary (Fig. 2C). The increased discharge of the tributaries and hillslopes that drain to the reversed segment further enhances fluvial erosion and sediment transport in the direction of the cliff, maintaining the asymmetry in slope across the divide (Fig. 2D).

The preferential divide migration mechanism gives rise to several predictions:

1. Reversal will occur when a valley is filled with a substrate that is more erodible than the interfluve. Where the erodible fill is absent, reversal is less likely.
2. A thicker fill for the same antecedent valley slope will sustain the slope imbalance across the divide over longer distances and enable further divide migration (Fig. DR7). Therefore, as long as the incision of the reversed channel occurs within the erodible fill, its length should scale with the thickness of this fill.
3. The preferential divide migration mechanism is independent of surface tilting. However, if tilting toward the cliff does occur, due to unique local conditions, it will increase the slope imbalance across the divide and expedite the rate of divide migration and reversal.

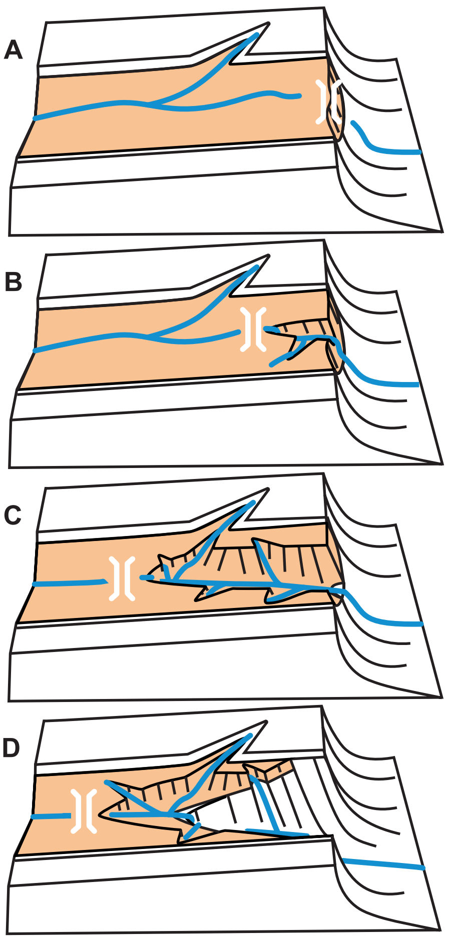

Figure 2. Cartoon showing the proposed drainage reversal mechanism by preferential divide migration within an erodible valley fill. Drainage is depicted in blue lines; brown regions mark the erodible valley fill; and white bridge-like symbol represents a wind gap. (A) When uniform cliff retreat truncates an antecedent channel and beheads its upper reaches, a sediment-filled saddle forms on the cliff (Fig. DR6A [see footnote 1]). The thickness of the fill likely reflects an interplay between the capacity of the antecedent basin to produce and carry sediments, and the more recent conditions that favor preservation and accumulation of colluvial and alluvial material due to the reduced discharge imposed by channel truncation. Here, the cliff and the water divide coincide, and slope imbalance between the cliff face and the antecedent channel promotes faster transport of erodible fill material down the cliff, inducing divide migration within the valley toward the highland. (B) A reversed segment is formed within the antecedent valley, bounded between the migrating divide and a waterfall that crosses the cliff. The fluvial incision within the erodible fill preservers the slope asymmetry across the divide and promotes further divide migration. (C) When the divide transverses a tributary confluence, the tributary joins the reversed channel and forms a barbed morphology. (D) As migration continues, the enhanced discharge of the reversed basin causes the waterfall to retreat and to embay the cliff.

FIELD AREA AND METHODS

We explore this preferential divide migration mechanism for reversal in basins that drain toward the western escarpment of the Dead Sea plate boundary in the southern Arava, Israel (Fig. 3A). We focus on an area of ~200 km^2 in the hyper-arid south Negev desert, which is bounded by the western Arava escarpment on the east (Fig. 3B). In this region, the Negev highlands are capped by a massive Cretaceous limestone. Here, the major divide mostly follows the escarpment edge. East of the escarpment, steep ephemeral basins drain east to the southern Arava Valley, and west of it, low-relief ephemeral channels flow westward. A map of χ,

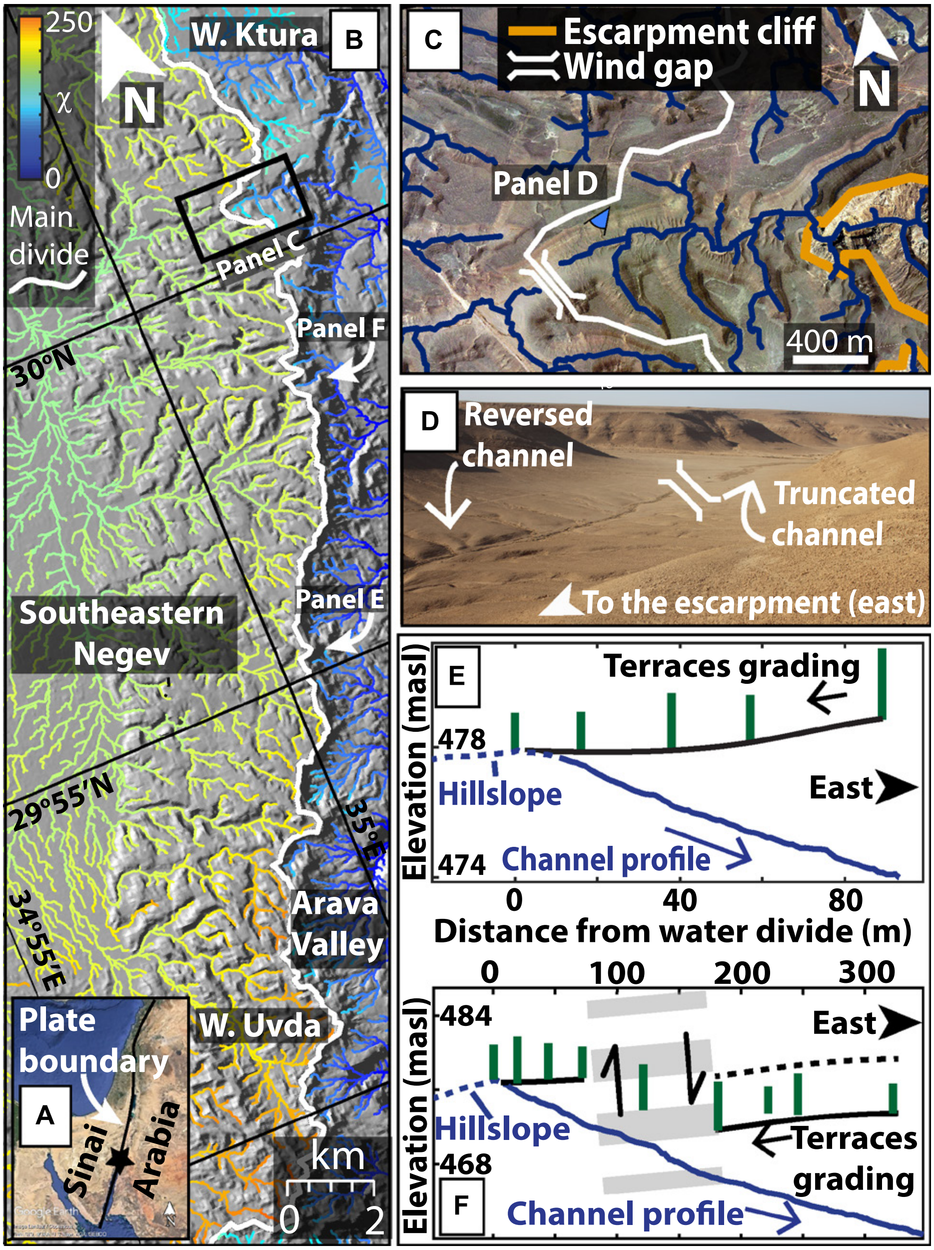

Figure 3. (A) Location map of the study area in Israel. (B) Shaded-relief map based on Advanced Land Observing Satellite (ALOS) Global Digital Surface Model (AW3D30) showing the escarpment, the major water divide, and the ephemeral drainage network color-coded by its χ value, where χ is a transformation parameter of horizontal distance along-channel scaled by the inverse drainage area (see Data Repository [see footnote 1]). Note the χ gradients across the main divide, which could be indicative of a non-equilibrium drainage basin geometry. Study area is bounded between Wadi (W.) Ktura and Wadi Uvda. (C,D) Aerial photo (C) showing looping of the water divide around a reversed highland channel that grades toward the escarpment edge. Note the shared valley with a west-grading, truncated channel on the other side of the wind gap that is shown in panel D. Blue "eye" symbol depicts the location and orientation from which the photo in panel D was taken. (E,F) Opposite gradients between east-grading channels and west-grading terraces along two highland channels that flow to the escarpment. Green bars represent the maximum and minimum elevation of each terrace (see aerial photos with mapped terraces in Fig. DR8 [see footnote 1]), and black curves show an interpreted continuous surface based on the lower extent of the terraces. masl—meters above sea level. (E) East Shaharut basin (number 25 in Table DR1; location in Fig. 3B), where the terraces form a single continuous surface that grades westward toward the wind gap and opposite to the active flow direction. (F) An upper reach of the Itro East basin (number 10 in Table DR1; location in Fig. 3B). Here, the terraces form two continuous surfaces that grade monotonically westward, whereas the active channel drains to the east. We propose that a normal fault, represented by the gray bars, mapped on the northern flank of the valley, lowers the eastern group of terraces by 5–6 m. Dashed black line shows the reconstructed elevation of the lower extent of the east terraces prior to faulting.

(a parameter that scales incremental distances along the channel by their inverse drainage area) shows large χ gradients across the main divide, with higher values on the west side (Fig. 3B). Such gradients could indicate an unstable divide prone for westward migration (Willett et al., 2014). Additional tectonic and geomorphic information about the study area is provided in the Data Repository.

We conducted field and remote-sensing surveys of the study area, mapped the escarpment and the divide, identified reversed basins, and mapped their geometry. We also documented the presence and thickness of erodible valley fill, and the grading direction of terraces and interfluves.

EVIDENCE FOR FLOW REVERSALS

Within the study area, we identified 38 channels that are oriented sub-perpendicular to the escarpment cliff and intersect it (Table DR1). Out of these, 19 channels grade to the west, so the divide that bounds their headwaters from the east coincides with the escarpment cliff. The remaining 19 channels grade east and cross the escarpment along waterfalls. In these cases, the main divide deviates westward from the cliff, loops around these channels, crosses the highland valley, and merges back with the cliff along the interfluves (Figs. 3B and 3C).

Three morphological attributes indicate that the latter 19 channels used to grade west and reversed their gradient while exploiting their antecedent valleys. First, five of the channels have barbed tributaries (Fig. 3C; Table DR1). Second, each of the east-flowing main trunks shares a wide valley with a west-grading truncated channel, which is part of the antecedent highland drainage network (Fig. 3C). These shared valleys host a flat divide, a wind gap, from which the flow diverges (Fig. 3D). Third, we've mapped fill-and-cut terraces of a mixed colluvial-fluvial origin (Fig. DR6) along two east-grading reversed channels (see the Data Repository, and Fig. DR8). In both cases, we found groups of terraces that form continuous surfaces that grade westward toward the wind gaps, away from the escarpment and opposite to the active channel direction (Figs. 3E and 3F). The observation of east-grading channels that incise into west-grading terraces indicates that the flow direction in these valleys has reversed.

SUPPORT FOR THE PREFERENTIAL DIVIDE MIGRATION MECHANISM

The first-order grading of the entire study area, as defined by a linear regression through the flat highland interfluves, shows a regional northwest trend (Fig. DR9A). This, together with the aforementioned westward grading of the terraces, suggest that any regional structural or tectonic tilt toward the east (Ginat et al., 2000)

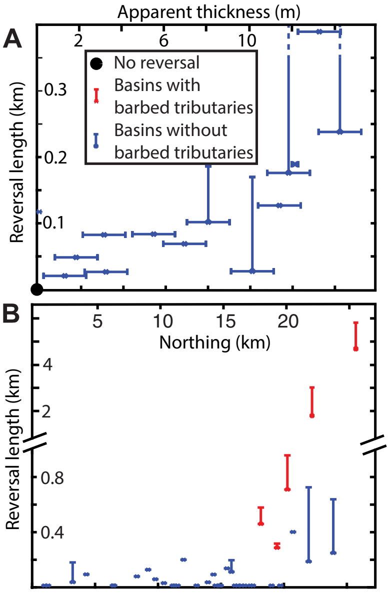

Figure 4. (A) Length of reversed channels versus apparent thickness of the erodible fill within channels (see Data Repository [see footnote 1]). Here, basins with barbed tributaries are omitted. Vertical error bars represent the uncertainty in length that is associated with the distance between the waterfall and the reconstructed cliff position (i.e., prior to cliff embayment). Horizontal error bars represent the uncertainty of the apparent thickness measurement due to DEM resolution. The observed correlation suggests that the thickness of the valley fill controls the extent of divide migration, and ultimately the length of the reversed channels, in agreement with the predictions of the preferential divide migration mechanism. See details of channel 31 in Table DR1 for local control on the data point near *y*-axis. (B) Length of reversed channels versus their northing position along escarpment from southern edge of study area (Wadi Uvda; see location in Fig. 3B). Red and blue symbols are for basins with and without barbed tributaries, respectively. Note scale difference across two sides of break in the *y*-axis. Longest reversed channels are concentrated in north part of study area.

is generally insufficient to reverse the slope of the highlands, and therefore is unlikely to have caused flow reversal in this area. Instead, several field observations support the applicability of the preferential divide migration mechanism for drainage reversal.

First, field and remote-sensing analysis indicates that 18 out of the 19 east-grading channels incise into thick (up to 30 m in places), erodible, terrace-forming sediments that cover the valleys floor (Fig. DR6). Conversely, the non-reversed west-grading channels that form saddles on the cliff are characterized by narrow headwaters and extremely thin fill (<1 m) or no fill at all in the proximity of the cliff. These observations fit the first prediction of the preferential migration mechanism, that reversal occurs where the valley is filled with erodible sediments.

Second, a geometric analysis of the east-grading channels reveals a positive correlation between the length of the reversed channels between the bounding wind gap and the waterfall and the apparent thickness (i.e., the elevation difference between the wind gap and the bedrock-fill interface; see the Data Repository) of the erodible valley fill (Fig. 4A). This correlation fits the second prediction of the preferential migration mechanism, that the length of the reversed channels scales with the thickness of the erodible fill.

Third, the longest reversed channels, including all of the channels with barbed tributaries, are located in the northern portion of the study area (Fig. 4B). A surface formed by spline interpolation based on the flat highland interfluves (Fig. DR9B) reveals a mild north to northeast tilting that is localized in the northeastern portion of the study area. This local tilt may contribute to the lengthening of the northern group of reversed channels (Ginat et al., 2000), in agreement with the third prediction of the preferential migration mechanism that tilting toward the escarpment expedites the rate of divide migration and reversal.

CONCLUSIONS AND IMPLICATIONS

Our field observations point at extensive drainage reversal that is associated with the migration of the main divide westward, in agreement with the prediction of the χ analysis (Fig. 3B). This migration is in line with the documented regional trend of expansion of the drainage area of the Negev desert that drains directly to the Arava Valley, following the late Cenozoic introduction of the Arava Valley base level (Avni et al., 2000). Drainage reversal, therefore, could play a critical role in redistributing drainages at the continental scale.

Reversal toward escarpments is particularly consequential for the escarpments' long-term evolution. The cause of variability in the preservation, morphology, and retreat rate between different escarpments has been a long-standing question (e.g., Prince et al., 2010; Braun, 2018; Duszyński et al., 2019; Godard et al., 2019), and highland drainage reorganization has been suggested to locally control the style and rate of escarpment retreat (e.g., Prince et al., 2010). More specifically, drainage reversals change the discharge, sediment flux (Pechlivanidou et al., 2019), and erosive power across an escarpment, and could alter the dominant escarpment retreat mechanism from cliff retreat to fluvial knickpoint retreat (Weissel and Seidl, 1998; Shelef et al., 2018).

The preferential divide migration mechanism is also applicable to local cliffs such as in capture settings, where a preexisting erodible valley fill (e.g., Prince et al., 2011, their figure 1) can promote reversal toward the new base level (Fig. 1). Our results, therefore, suggest that reversals could be independent of tectonic forcing and could be a direct consequence of valley truncation that preserves valley fill (Yang et al., 2015). This means that the presence and thickness of erodible valley fill is consequential for channel susceptibility to drainage reorganization.

Whereas this work highlights the influence of erodible valley fill on drainage reorganization, we note that other settings and processes could lead to a similar result. For example, antecedent channels incised into erodible bedrock, or preferential groundwater discharge on the steep side of divides (e.g., Pederson, 2001; Brocard et al. 2011), could cause preferential divide migration within antecedent valleys. Further field and numerical exploration of the sensitivity of divide migration to local conditions can shed light on the influence of such conditions on large-scale cliff and landscape evolution.

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