Episodic bedrock strath terrace formation due to meander migration and cutoff

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ABSTRACT

In order to explore mechanisms of bedrock terrace formation, we have developed a numerical model that couples vertical river incision and meandering. Model results illustrate that flights of unpaired strath terraces can form purely from the internal dynamics of bedrock river meandering in vertically incising channels. Specifically, knickpoints that propagate upstream following meander cutoffs enhance vertical incision, whereas channel lengthening and corresponding slope reduction during meander growth suppresses vertical incision. Analysis of topography from the Smith River, Oregon, USA, suggests terrace formation by this mechanism. Our results introduce an alternative mechanism to climatic or tectonic forcing, namely inherent instability triggered by meander growth and cutoff, that explains both oscillations in rates of vertical bedrock incision and the formation of longitudinally traceable, unpaired bedrock terraces. In addition, our results point to simple topographic criteria for identifying internally generated fluvial bedrock terraces.

INTRODUCTION

In many actively incising river canyons, gravel-capped bedrock (strath) terraces occur tens to hundreds of meters above the active channel and extend discontinuously for kilometers, often paralleling the river profile. Long recognized as recording the former river bed elevation, strath terraces, when dated, provide a direct means of quantifying rates of vertical bedrock river incision and are thus vital to studies of geomorphology and active tectonics (e.g., Lavé and Avouac, 2000; Molnar et al., 1994; Pazzaglia and Brandon, 2001). Strath terraces are generally distinguished as either unpaired (terrace present on only one side of the active channel) or paired (terraces present on both sides of the active channel at the same elevation). Here we primarily consider the process of unpaired strath terrace formation because unpaired terraces are more commonly observed in nature (e.g., Personius et al., 1993).

Flights of unpaired strath terrace treads and risers adjacent to channels form stepped topographic profiles, frequently located on the inside of bedrock river meanders (e.g., Personius et al., 1993). Terrace treads generally slope gently toward the direction of river migration, suggesting that the ratio of vertical incision rate to lateral incision rate is low during periods of strath planation. This topographic evidence is supported by measured lateral planation rates in rivers with strath terraces that are one to two orders of magnitude higher than typical vertical bedrock incision rates (Fuller et al., 2009; Stock et al., 2005; Suzuki et al., 1983). Steep or near vertical terrace risers, in contrast, imply that intervals of dominantly lateral erosion are apparently punctuated by periods of relatively high vertical incision rate.

Explanations for why many incising rivers alternate between periods of dominantly lateral and dominantly vertical incision generally appeal either to temporal variation in base-level stability or in the volume of coarse sediment supplied to rivers. For example, because gravel deposition in rivers armors the bed and suppresses vertical incision (Gilbert, 1877; Sklar and Dietrich, 2004), some propose that lateral channel shifting and strath terrace formation is favored during climatic periods of higher sediment supply relative to river transport capacity, whereas vertical incision is favored when sediment supplies are low relative to transport capacity (e.g., Hancock and Anderson, 2002; Molnar et al., 1994). Alternatively, because base-level stability forces a river to remain at one elevation, others propose that either tectonic quiescence punctuated by impulsive uplift (Davis, 1902) or sea-level rise and fall superimposed on steady tectonic uplift (e.g., Pazzaglia and Gardner, 1993) can generate flights of strath terraces. Although it is acknowledged that strath terraces might also be generated internally (Bull, 1990), that is, in the absence of a change in external forcing, no specific mechanism for so-called "complex-response" terraces has been offered.

A persistent obstacle to interpreting the tectonic and paleoclimatic significance of strath terraces is that development of a mechanistic model for lateral bedrock erosion has proven challenging (Hancock and Anderson, 2002; Montgomery, 2004; Suzuki, 1982). Because the process of lateral erosion is uncertain, the paleoclimatic and/or tectonic significance of strath terraces remain unclear.

In contrast to rivers incising through rock, lateral translation in alluvial rivers is more clearly understood. To maintain meandering, bank strengths must be high enough to retard migration rates so that they are comparable with point bar deposition rates, but not so high that the bank cannot be eroded during flooding of the channel (Braudrick et al., 2009). Here we hypothesize that these conditions can also be met in rivers that incise highly weathered or fractured bedrock, where detachment of rock from the channel banks can occur from fluid stresses alone. Rivers with strath terraces, in addition to cutting weak and/or highly fractured rocks (e.g., Montgomery, 2004; Suzuki et al., 1983), also commonly display evidence for meandering (e.g., Personius et al., 1993; Shyu et al., 2006). The Smith River in Oregon (United States) for example, is a meandering bedrock river in a region where strath terraces are documented (Personius et al., 1993), and evidence for bedrock meander loop cutoffs is clear in the topography surrounding the river (Fig. 1A). The presence of bedrock meander loop cutoffs, in particular, indicates that meandering can occur actively in rock (Harden, 1990; Hovius and Stark, 2001), and that where bedrock cutoffs are found, meanders are not simply inherited from an antecedent alluvial river, as is commonly inferred (e.g., Davis, 1893; Rogers et al., 2002).

In a meandering bedrock channel without vertical incision, alluvial deposition causes the inner bank to follow the outer bank's lateral shifting, creating an alluvium-mantled bedrock surface (later to become a strath surface if there is a pulse of vertical incision). Alternatively, inner bank accretion may lag outer bank erosion such that with lateral shifting the channel effectively widens, favoring a braided alluvial channel form (even when the outer bank is sharply curved). Braiding should tend to reduce flow against the outer bank and hence lateral shifting. Therefore, the presence of loop cutoffs (e.g., Fig. 1A) appears to require an inner bank that matches outer bank shifting, as in a meandering alluvial river.

Meandering in fractured and/or weathered bedrock combined either with point bar deposition or, with progressive vertical incision, an outward-sloping bedrock bank on the inside of a bend, provides a simple mechanism for driving lateral motion of a river into rock without it significantly

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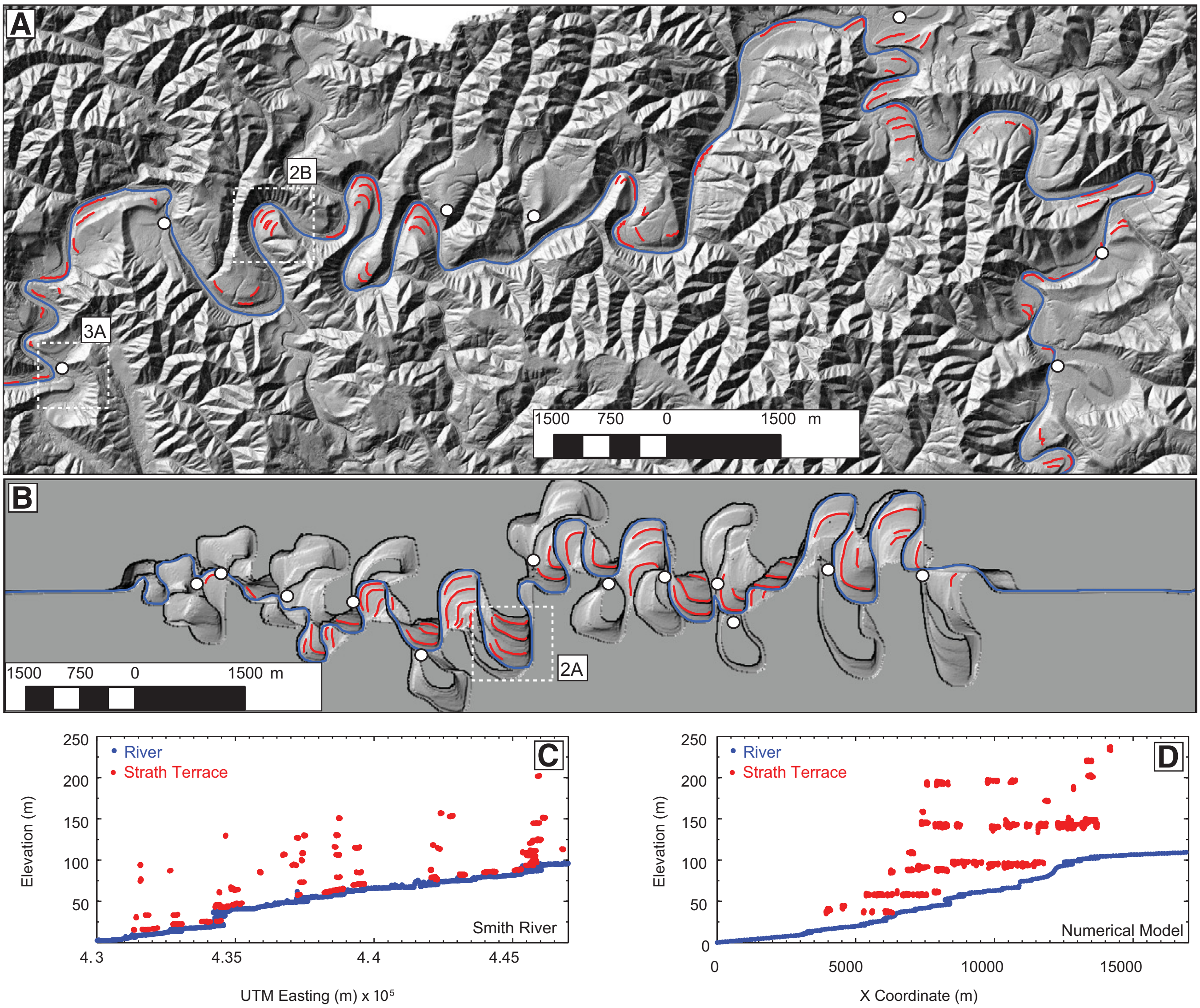

Figure 1. A: Shaded relief image of Smith River, Oregon (United States) and surrounding topography from 1-m-resolution LIDAR data. B: Shaded relief image of 10-m-resolution numerical model output. In A and B, locations of bedrock meander cutoffs are identified with white dots, and outside edge of strath terrace treads are shown in red; river flow is from right to left. Locations of Figures 2A, 2B, and 3A are indicated with white boxes. C and D: River elevation profile (blue) and strath terrace elevations (red) from A and B, respectively, projected onto east-west–striking plane. UTM—Universal Transverse Mercator.

changing channel width (Yagi and Ikeda, 1997). In addition, meandering dynamics supply a mechanism for incising and hence generating strath terraces. Specifically, by excising sections of the river long profile, meander loop cutoffs create elevation discontinuities (i.e., knickpoints) along the channel profile, thereby locally steepening the channel and potentially increasing its incision rate. Such steepened reaches, in turn, may propagate upstream as a wave of vertical incision.

To explore the consequences of loop evolution and cutoff on strath terrace development, we combine an existing model for bend evolution (Howard and Knutson, 1984) with an existing model for boundary shear stress–driven river incision into bedrock (Howard and Kerby, 1983) (GSA Data Repository[1]). We propose that the details of the lateral and vertical erosion processes, which are not treated mechanistically here, are not necessary to reveal the dynamic consequences of periodic loop cutoff on strath terrace formation. While we present quantitative comparisons with the Smith River, this comparison is meant only to show that model results provide a possible alternative explanation for unpaired strath terrace formation on the Smith.

RESULTS

A shaded relief map generated from a simulation with coupled meandering and vertical incision reveals the topographic record left from an incising meandering river (Fig. 1B). Visual comparison of the numerical model output with high-resolution LIDAR–derived topographic data from the Smith River shows that the morphology and spatial distribution of both unpaired strath terraces and meander cutoffs in the model are similar to those of the Smith River (Figs. 1A and 2B). The presence of stepped meander bends in our model (Figs. 1B and 2A) and in the field (e.g., Shyu et al., 2006) (Figs. 1A and 2B) shows that periods of primarily lateral

[1]GSA Data Repository item 2011068, numerical model development, strath terrace identification, and Movie DR1 (an animation of the numerical model), is available online at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

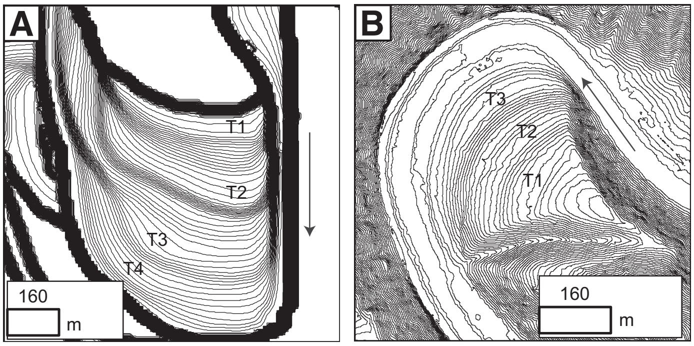

Figure 2. Contour maps of stepped meander bend. A: Derived from coupled numerical simulation. B: Derived from Smith River LIDAR data. Strath terraces are labeled as T1–T4 (oldest to youngest). Contour interval is 3 m in all images. Black arrows in A and B indicate river flow direction.

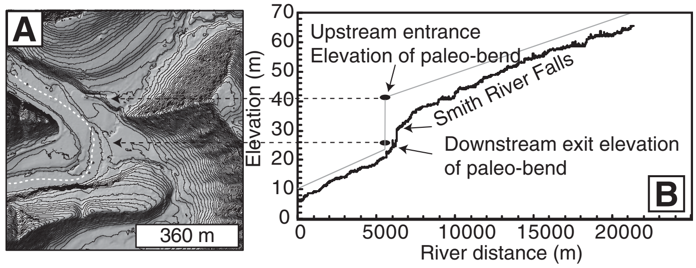

Figure 3. A: LIDAR-derived shaded relief image of recent meander neck cutoff on Smith River, also shown in Figure 1A. Contour interval is 3 m. B: LIDAR-derived river elevation long profile upstream and downstream of cutoff shown in A. Black ovals indicate location and elevation of entrance and exit of former meander bend. Gray line indicates inferred channel elevation long profile immediately following meander bend cutoff.

planation associated with meander growth are periodically interrupted by intervals of dominantly vertical erosion. In the model, bedrock steps form when knickpoints propagate upstream through a growing meander bend and thus locally increase the rate of vertical incision (Movie DR1 in the Data Repository). Knickpoints, which are generated only from cutoff meanders in the model, propagate upstream by as much as ~10 km through the domain (Fig. 1D; Movie DR1). In the model, the slope break that marks the transition from a terrace tread to a terrace riser (Fig. 2A) thus records a pulse of enhanced vertical incision associated with a propagating knickpoint generated from a downstream meander cutoff. The height of the terrace riser below this slope break is, in turn, controlled by the height of the propagating knickpoint (Movie DR1).

During time intervals between propagating knickpoints, the vertical incision rate of a given river reach decays as meander growth proceeds, channel length increases locally, and slope declines. Simultaneous channel meandering and upstream-propagating incision waves in the model thus generated longitudinally traceable, unpaired strath terrace levels along the walls of the river canyon (Fig. 1D). Each laterally traceable terrace level in Figure 1D records a pulse of higher vertical incision rate triggered by a passing knickpoint generated from a downstream cutoff. A comparably sized reach of the Smith River shows a similar pattern and distribution of mapped strath terraces and meander cutoffs (Fig. 1C) (although terrace profiles are apparently not as flat-sloped or as continuously well defined).

Because terraces are abandoned when a knickpoint propagates upstream, terrace surfaces are time-transgressive in the model. Considerable lowering of the entire channel network (i.e., not just where there are knickpoints) therefore occurs as the knickpoint propagates through the model domain. Consequently, a knickpoint is at a lower elevation in the upstream reaches of a channel than it otherwise would if the channel weren't lowering. Because the terrace tread slope is defined by the trajectory of the knickpoint crest as it moves upstream, terrace treads in the model slope much more gradually than the active channel (Fig. 1D).

If unpaired terraces are created from meander migration and cutoff along a river, evidence for cutoff meanders should be present in the topography surrounding the river.

Our survey of LIDAR data from the Smith River reveals numerous bedrock meander cutoffs in the topography surrounding the Smith River (Fig. 1A), indicating that here meandering might plausibly trigger terrace formation. The mechanism for strath terrace generation and abandonment that is described here also predicts that propagating knickpoints should be present upstream of meander cutoffs. To test this prediction, we analyzed high-resolution topographic data from just upstream of the most prominent recent meander cutoff on the Smith River (Figs. 1A and 3A), known locally as the "The Island," to look for evidence of knickpoint propagation. The LIDAR data reveal a series of bedrock cascades (Smith River Falls) that drop in total about the same amount as the elevation change around the ~6 km bend that forms the cutoff (Fig. 3B), suggesting that the knickpoint in this location was triggered by the cutoff meander located just downstream. Notably, the estimated elevation drop around 27 current and abandoned bedrock meanders on the Smith River ranges between 5 and 15 m (Fig. 4). This elevation range is comparable to terrace riser heights on the Smith River (e.g., Fig. 2B) and reported for other rivers in the Oregon Coast Range (Personius et al., 1993), which is what would be predicted if terrace treads were incised by knickpoints triggered from cutoff bedrock meanders.

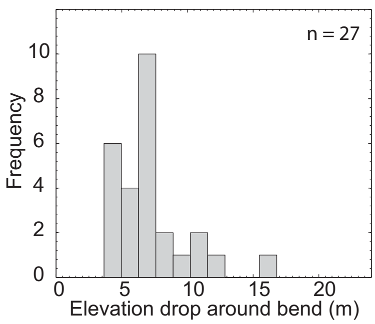

Figure 4. Histogram of estimated elevation drops measured around 27 active and abandoned bedrock meander bends. To generate histogram we multiplied distance around each bend by average channel gradient of Smith River, 0.003.

DISCUSSION AND CONCLUSIONS

Our findings show that in sinuous bedrock channels where meander cutoffs occur, repeated bedrock river meander growth and cutoff drives internal oscillations about a mean value in the channel slope and therefore in the rate of vertical incision. The presence of unpaired strath terraces along a meandering river is therefore not sufficient to make inferences about climatic or tectonic forcing. Rather, our results illustrate that the internal dynamics of meander migration and cutoff can also generate pulsed incision (Figs. 2A and 2B), locally large knickpoints (Figs. 3B and 4), and longitudinally traceable unpaired strath terraces along a river (Figs. 1C and 1D).

Our model makes several testable predictions regarding the influence of internal dynamics on unpaired strath terrace genesis. In particular, where unpaired strath terraces form due to the internal dynamics of meandering, evidence for meander cutoffs should be present in the topography surrounding the river (e.g., Fig. 1A). In addition, the height of strath terrace risers should be comparable to the elevation drop around bedrock meander bends (e.g., Fig. 4) and knickpoints should be present upstream of recent bedrock meander cutoffs (Fig. 3B). If strath terraces are locally less steep than the mean channel slope (e.g., Fig. 1D), this would also be consistent with our model (or any other model in which propagating knickpoints are responsible for bedrock terrace abandonment).

Because our model channel has a fixed width and moves both laterally and vertically at all times in the simulation, paired strath terraces were never formed in the numerical model. The creation of longitudinally continuous paired strath terraces (e.g., Molnar et al., 1994) therefore appears to require changes in the width of the active channel. For example, paired strath terraces might record transitions from braided to single thread channels (Hancock and Anderson, 2002). Alternatively, paired straths could record the upstream passage of propagating knickpoints, which can cut slots that are narrower than the channel upstream (e.g., Yanites et al., 2010). Thus, in our model relaxation of either the fixed channel width assumption or the single thread channel assumption might yield insight into processes of paired terrace formation. However, the fact that paired straths are less commonly observed than unpaired straths (e.g., Personius et al., 1993) indicates that in many settings dynamic adjustments in active channel width need not be invoked to explain strath terrace genesis.

Several mechanisms exist for generating knickpoints in meandering channels (e.g., Frankel et al., 2007; Seidl and Dietrich, 1992). In addition, if knickpoints are diffusive or stationary (Seidl and Dietrich, 1992), then strath terraces formed from our proposed mechanism might be limited to a discrete zone upstream of a cutoff, or perhaps not present at all. We therefore emphasize that our goal here is not to offer a comprehensive explanation for unpaired strath terraces along the Smith River (and elsewhere). Rather, our goal is to show how unpaired strath terraces can form entirely as an instability triggered by bedrock river meandering. We note that belts of uplifted clastic sedimentary rocks, where strath terraces and bedrock river meanders are commonly observed, compose wide swaths of most active mountain ranges on Earth. Given the instabilities that are inherent to these meandering channels, we therefore question the potential fidelity of such rivers as recorders of climatic and tectonic events.

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