A lithologic control on active meandering in bedrock channels

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ABSTRACT

Topographic evidence requires that some rivers actively meander in bedrock, yet the way in which rivers can erode laterally and meander within bedrock banks is not well understood. Lateral channel migration, and especially lateral channel migration via active bedrock meandering, is commonly responsible for the preservation of unpaired strath terraces. A process-level understanding of lateral channel migration and active meandering in bedrock rivers is key to interpreting the climatic and tectonic significance of unpaired strath terraces and the planform shape of bedrock rivers. In this study, we compare erosional processes in two adjacent bedrock channels in the Santa Cruz Mountains, California. The main differences between these channels are that Pescadero Creek actively meanders within mudstone, while Butano Creek is straight and incises sandstone. Laboratory rock strength and slake durability tests show that while the two lithologies have similar tensile strengths before drying, the meander-supporting mudstone loses strength dramatically when dried and rewet (slakes), while the sandstone does not. The slaked mudstone bank rock was easily detached without the need for bedload tools during in situ erosion tests, while mudstone that had not dried and sandstone were not detachable. The depth of bank rock detached solely from rewetting of previously dried mudstone ranges between 1 and 8 mm, which is well in excess of annual background erosion in the Santa Cruz Mountains. In addition, hand samples of the mudstone rapidly disintegrated upon wetting and drying in the laboratory, whereas sandstone hand samples remained intact. In the meandering stream, there is a consistent pattern of scoured bedrock (exposed to drying and slaking) along the outside "cutbank" of meander bends and forced bars that grade into soil and vegetation, which protect the bedrock from slaking along the inside of bends. Additionally, in the meandering stream, subaerially exposed mudstone clasts are often found to be disintegrating on the surface of bars. Taken together, these observations suggest that slaking allows for bedrock meandering in two fundamental ways. First, by rapidly disintegrating coarse hillslope-derived sediment that is deposited in the channel, slaking suppresses the negative feedback on lateral channel migration that would otherwise result from the buildup of talus along a retreating bedrock valley wall on the outside of a meander bend. Second, at cutbanks where scour exposes bare bedrock to drying, slaking weakens a layer of bank rock to the point where it can be eroded by clear-water flows. In these ways, slaking enables erosion into bedrock banks in response to curvature-driven fluid shear stress perturbations, as in alluvial rivers.

INTRODUCTION

Despite the common argument that meanders in bedrock canyons reflect an antecedent alluvial condition (Davis, 1893, 1899; Dury, 1965, 1972), many sinuous bedrock rivers exhibit topographic evidence requiring that the active development of sinuosity occurred during vertical bedrock incision (Finnegan and Dietrich, 2011; Harden, 1990; Hovius and Stark, 2001; Lavé and Avouac, 2000; Shyu et al., 2006; Tinkler, 1972; Winslow, 1893). This evidence includes: (1) cutoff bedrock meander bends at various elevations above the modern channel that show that meander growth occurs in bedrock (Fig. 1A); (2) bedrock strath terraces that line the inside of meander bends and increase in their radius of curvature toward the modern river channel, and thereby record active bend growth during vertical incision (Fig. 1B); and (3) asymmetric valley cross sections at meander bend apexes that demonstrate faster hillslope lowering along the steeper outer cutbanks than the shallower inner banks of meander bends, independent of orientation of the bend to bedrock structures (Fig. 1C).

Unpaired strath terraces are important records of past river location and as such provide important tectonic and climatic records (Finnegan and Dietrich, 2011; Lavé and Avouac, 2000; Merritts et al., 1994; Personius et al., 1993; Shyu et al., 2006). Most strath terraces form in weak sedimentary rocks that are prone to slaking (Montgomery, 2004). Lateral mobility in actively meandering bedrock channels provides a key mechanism for preserving unpaired strath terraces along the inside of bends (Finnegan and Dietrich, 2011; Lavé and Avouac, 2000; Personius et al., 1993; Shyu et al., 2006). However a mechanistic link between slaking and bedrock river meandering has not been demonstrated. In addition, bedrock channel sinuosity may itself hold clues about past climatic forcing (Limaye and Lamb, 2014; Stark et al., 2010). Despite the importance of landforms associated with actively meandering bedrock rivers, little is known about the process by which a river can erode laterally into bedrock and meander. Without a process-based understanding of bedrock meandering, we lack specific knowledge that is key to interpreting strath terraces and sinuous bedrock river valleys.

In contrast to bedrock channels, the process of meandering in alluvial channels is better understood. Meanders emerge from a tight coupling between bank erosion and near-bank flow velocity (Howard, 1992; Parker et al., 1982). Specifically, when flowing water is forced around a curved bank, centrifugal acceleration that results from this forced change in flow direction pushes the high-velocity core of the stream closer to the outer bank, causing a steeper velocity gradient there. Likewise, this leaves the velocity gradient at the inner bank much more gradual. Shear stress is controlled by this velocity gradient, resulting in an increase in shear stress along the outside of bends and a relative reduction in shear stress along inner banks relative to a straight channel (Dietrich et al., 1979; Einstein, 1926; Ikeda et al., 1981; Leopold and Wolman, 1960). Thus, coming into a bend, stress decreases on the inside bank and increases on the outside bank. These stress divergences result in erosion on the outer bank and deposition of a point bar along the inner bank, and therefore lateral growth of a constant-width meander bend can result (Dietrich et al., 1979; Leopold and Wolman, 1960; Parker et al.,

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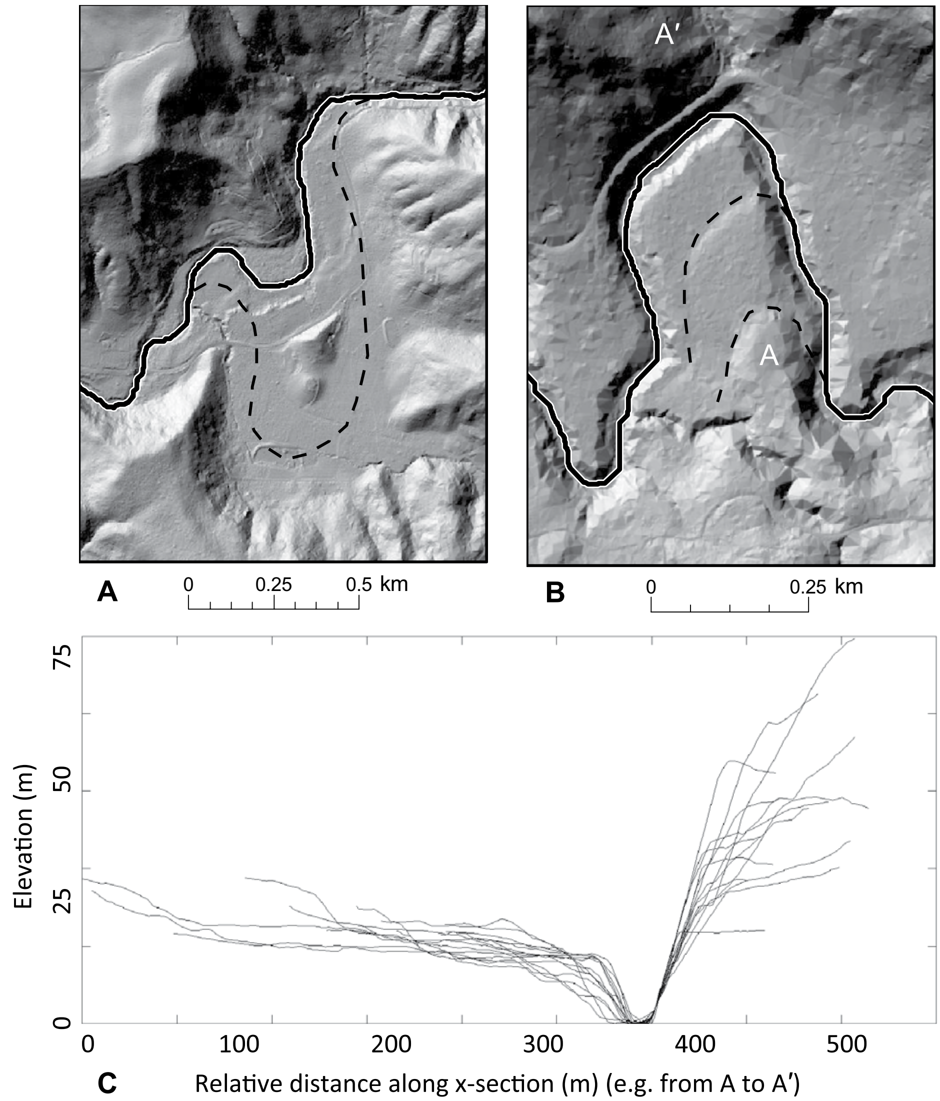

Figure 1. Topographic evidence for active meandering in Pescadero Creek: (A) cutoff meander bend (the solid line is the modern channel, and the dotted line is the past river path); (B) strath terraces along the inside of a bend track outward growth of a meander bend toward the modern channel; and (C) asymmetric valley walls that are steeper at cutbanks and more gradual along the inside of meander bends (cross sections were taken across the apex of every bend shown in Figure 6A from left to right across the convex to concave banks).

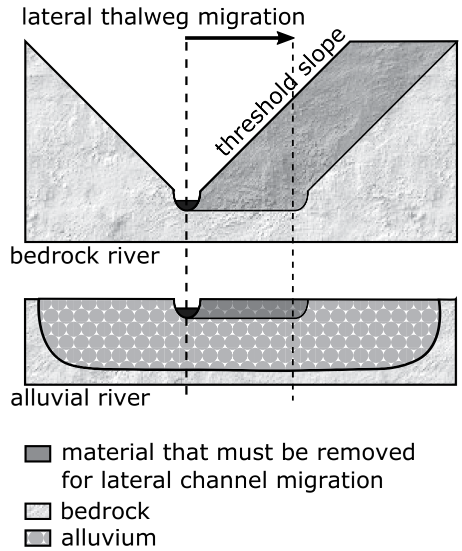

Figure 2. Lateral channel migration into bedrock valley walls requires transport of more material than lateral channel migration on a floodplain, where, in addition, material is alluvium rather than colluvium (and therefore a transportable size by definition). Colluvium from steepened valley walls could provide a strong negative feedback on lateral bank migration. In A and B, flow is from right to left, north is up.

2011). In this way, the spatial variation of erosion and deposition in a meandering alluvial river is controlled by the response of fluid flow to channel curvature.

Regardless of the channel boundary composition, a curved channel will cause the same spatial patterns in shear stress. However, there are two specific challenges to meandering within bedrock as compared to alluvial banks: (1) Alluvium is, by definition, of a grain size that is erodible and transportable by fluid shear stress, while bedrock can have a prohibitively high threshold for detachment, and (2) the low-relief geometry of an alluvial floodplain leaves much less material to be moved per unit of lateral channel migration than in a bedrock canyon, where a whole valley wall stands in the way of a laterally migrating channel (Fig. 2). This eroded bedrock valley wall material, when deposited in the stream, could provide a strong negative feedback on lateral channel migration by filling the channel with talus and armoring the outside bank against further lateral erosion or even reversing lateral motion (Fig. 2).

Sharp changes in the sinuosity of bedrock rivers across lithologic boundaries (such as the one pictured in Figure 3 along Butano Creek, California) motivated us to explore the hypothesis of a lithologic control on bedrock river meandering. Stark et al. (2010) also reported that a trend in the relationship between climate and bedrock river sinuosity is only significant in certain rock types. In this paper, we explore rock properties that might allow for fluid shear-stress–driven lateral erosion of bedrock banks.

Montgomery (2004) proposed that the low slake durability of some lithologies could result in channel widening. Slaking, the loss of rock strength during cycles of drying and rewetting, could weaken some types of bank rock between high and low water levels and thereby encourage lateral erosion. Stock et al. (2005) directly observed channels widening via slaking, and Hancock et al. (2011) observed that more easily weathered rocks have wider channel cross sections than unweathered rock. Here, we ask if slaking could accommodate bedrock meandering, instead of widening, by allowing for erosion only at the concave leading bank of meander bends. Specifically, we test the hypotheses that slaking (1) renders bedrock susceptible to erosion by fluid flow along just the cutbank of meander bends and (2) rapidly reduces the grain size of colluvium (sourced by lateral incision into threshold canyon walls), allowing for efficient fluvial transport. Herein, we argue that lithology imparts a first-order control on

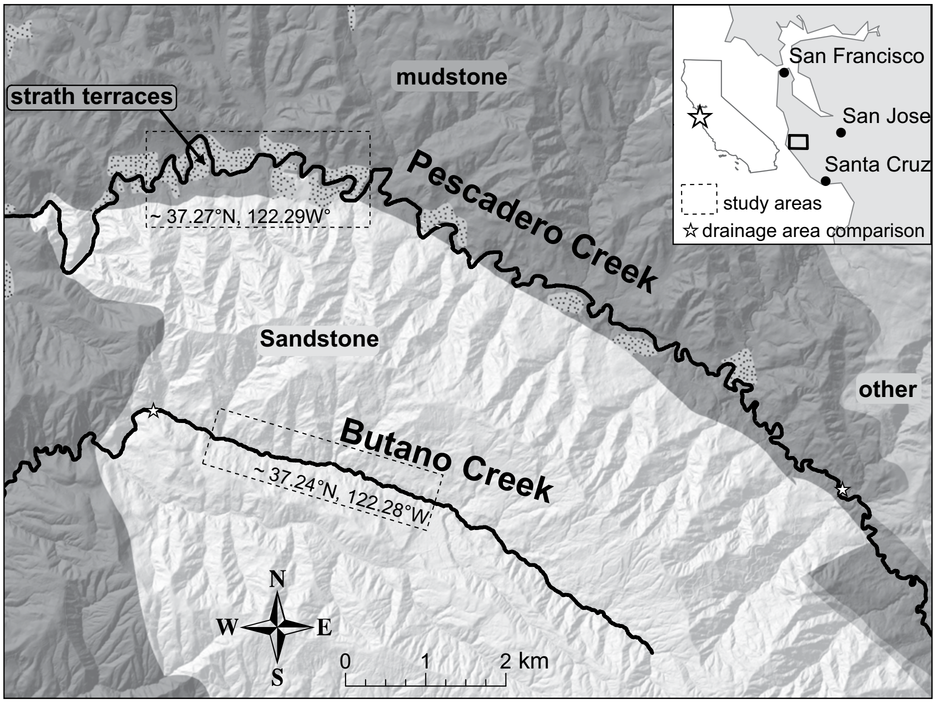

Figure 3. Pescadero and Butano Creeks are ~70 km south of San Francisco within the Santa Cruz Mountains, California. Pescadero is incising through the Purisima Formation mudstone and has a sinuous planform. Butano Creek to the south is incising through the Butano Sandstone and has a straight planform upstream of the mudstone contact. Mudstone bedrock is shown in dark gray, sandstone in white, and strath terraces in dotted gray.

bedrock meandering, and therefore an understanding of lithologic properties is the essential foundation for a mechanistic understanding of the bedrock meandering process.

EXPERIMENTAL DESIGN

Natural Experiment

In order to test for a lithologic control on meandering in bedrock rivers, we exploited a natural experiment within California's coastal Santa Cruz Mountains (Fig. 3) that isolates the effects of lithology on bedrock meandering. Pescadero and Butano Creeks are adjacent streams located near the town of Pescadero, California, ~70 km south of San Francisco. Pescadero Creek is a sinuous bedrock stream with evidence for active meandering (as described earlier; Fig. 1). Pescadero Creek has a 154 km^2 drainage area at its mouth and has an average channel slope of 0.3% within the reach considered here. It is incising into the mudstone Tehana Member of the Purisima Formation, a late Miocene continental shelf and slope deposit (Branner et al., 1909; Powell et al., 2007). Bed load in Pescadero Creek, however, is predominantly made up of more competent lithologies, including sandstone and a variety of metamorphic lithologies sourced far upstream from a small portion of the watershed.

The adjacent low-sinuosity Butano Creek shows no such evidence for active meandering and is incising into Butano Sandstone, a mid-to-lower Eocene deep-sea fan deposit (Critelli and Nilsen, 1996). Butano Sandstone makes up most if not all of the sediment in the channel. Butano Creek has a 56 km^2 drainage area at its mouth and has an average channel slope of 1.5% within the reach considered here. Although Butano Creek has a smaller drainage area than Pescadero Creek at our study sites, Pescadero Creek exhibits all the signs of active bedrock meandering at even smaller drainage areas than our Butano study area (Fig. 3). This, in combination with the rapid transition from a straight to a sinuous channel that occurs where Butano Creek enters mudstone downstream of our study site (Fig. 3), makes us confident in assuming that meandering here is not simply a function of drainage area.

Specific similarities between Pescadero and Butano Creeks enable these streams to be used as a controlled natural experiment. Both streams fall within a xeric climate regime with dry summers and a winter rainy season with an average of 1 m of rainfall per year (PRISM Climate Group, 1981–2010) concentrated into distinct storm events, separated by dry conditions. Stage data from a U.S. Geological Survey (USGS) gauging station on Pescadero Creek ~6 km downstream of our study site indicate that during an average year, ~4–8 storm events raise the stage at least 0.5 m, and most years the stage increases up to 3 m above base flow at least once (USGS, 2014). Butano Creek has no gauge, but given the proximity to Pescadero Creek, the storm events that drive Pescadero's hydrograph should also drive Butano's hydrograph. Although flow depths should scale according to the slightly different drainage areas at our study sites, important factors such as valley orientation to prevailing weather systems and vegetation communities are the same and should lead to similar wet and dry events. Winter climate in coastal California can be highly variable year to year. Summer climate, however, is consistently dry, and both Pescadero and Butano Creeks are perennial streams (groundwater fed during the summer dry season).

Relative uplift rates are controlled because both streams share a common base level within an estuary (Pescadero Lagoon) and exist within the same tectonic subblock (the La Honda subblock) of the Santa Cruz structural block (Powell et al., 2007), within the Santa Cruz Mountain transpressional zone (Anderson, 1990; Bürgmann et al., 1994). Both watersheds are forested with coastal redwoods, helping to control for the effects of vegetation on erosion and sediment input.

Lithology is the main difference between these two drainages, and therefore we used this natural experiment to isolate the effects of lithology and rock mechanical properties on the processes that control planform shape in these streams. Specifically, we tested if slaking is the lithologically controlled erosion mechanism that occurs in Pescadero Creek but not in Butano Creek and renders only Pescadero Creek susceptible to meandering.

METHODS

We tested the predictions of our two hypotheses using the Pescadero-Butano natural experiment in both the laboratory and field.

Can Slaking Enable Clear-Water Erosion of Bedrock?

Tensile Strength Measurements

Resistance to erosion (via abrasion wear) scales with rock tensile strength (Sklar and Dietrich, 2001), and because rocks are weakest in tension, tensile strength is the most relevant measure of bedrock resistance to fluvial erosion. We used measurements of tensile strength before and after one drying-rewetting cycle to quantify the change in strength induced by slaking for our two field lithologies. To this end, 90 1-in.-diameter (~2.54-cm-diameter) cores were drilled and cut from rock that had never experienced drying (collected from below base-flow water level) at sites along both Butano and Pescadero Creeks. Half of these cores were kept wet while the others were dried for 48 h and then rewet for 48 h. All cores were then subjected to the Brazilian tension splitting test (Vutukuri et al., 1974).

In Situ Erosion Tests

Even the weakest rock types have tensile strengths that are larger than the typical magnitude of fluid shear stresses exerted by a river on its boundary (Sklar and Dietrich, 2001). Nevertheless, we hypothesize that meandering results from a process that requires tight coupling between fluid flow and boundary erosion. Therefore, we tested whether bank rock in either stream is ever susceptible to clear-water erosion in the absence of abrasive tools. We did this in situ because we found that detached clasts exhibit a very different slaking behavior than in situ bedrock (as discussed in detail later herein), making bank rock slaking difficult to mimic in a laboratory setting.

Impinging water jets are commonly used to generate in-stream boundary shear stresses along exposed alluvial riverbanks (Hanson and Cook, 2004). We calibrated two handheld water jets (a large squirt gun, and a hand fire pump) and used them to apply fluid shear stress to rock along the banks of Pescadero Creek and Butano Creek. The calculation of shear stress from an impinging water jet is extremely sensitive to variations in the diameter of the stream of water emitted from the jet, the initial jet speed, the choice of the empirical coefficient for roughness of the bedrock surface, and the decay of shear stress outward (Hanson and Cook, 2004). Because of the difficulty in measuring these quantities to sufficient accuracy, we instead chose to normalize detachment from our jets to the most detachable site and use these data as a relative measure of detachability between our two rivers. We measured erosion for bedrock at the summer (dry season) low water line, where, though rock is not underwater, it is observed to be saturated. We also measured erosion of bedrock higher on the bank, where it is dry during the summer. Rock detached by the jets at each site was collected, dried, and weighed.

We also performed an end-member test to measure detachment simply due to rewetting of dried bedrock in the absence of a current. At the tail end of a late-season storm, we selected sites along Pescadero Creek where massive unslaked mudstone was exposed after any rind of slaked rock had been cleaned away by the storm flows. During the dry season, we returned to these sites and sealed a 15-cm-diameter cylinder to the bank to hold water over the dried area. After resaturating rock for ~10 min, we collected detached sediment and dried, weighed, and then calculated the volume of eroded material using the measured dry bulk density of local preslaked bank rock (2.08 g/cm^3). Volumes were converted to linear erosion per unit area. These measurements aim to provide a bound on bank-rock slaking detachment after one dry-rewet cycle.

Mapping of Bedrock Exposure

In order to connect the spatial distribution of slaking erosion to meandering, we mapped the pattern of bedrock exposure in Pescadero Creek. Butano Creek was not mapped because slaking was not found to occur there (see Results). Mapping was carried out on a 2-m-contour-interval topographic map derived from 1 m spot spacing light detection and ranging (LiDAR) data flown for San Mateo County in fall of 2005. Bedrock exposure and signs of slaking (Fig. 4A) were mapped along with bar deposits and locations where bedrock was not exposed due to reasons other than a bar deposit, for example, where soil extended to base-flow water level. The thalweg was also mapped in the field in finer detail than LiDAR could resolve. In total, we mapped eight meander bends in Pescadero Creek (~7 km).

Does Persistent Colluvium Buffer Against Lateral Bank Erosion?

Field Mapping

Lateral migration of a bedrock valley wall requires the production of colluvium (Fig. 2). If persistent when deposited in the channel, this hillslope-derived material can provide a negative feedback on further bedrock bank erosion. To determine the extent to which colluvium persists in Pescadero Creek, we mapped sources of colluvium (such as bedrock bank failures, rock fall sources, and landslide scarps). We also looked for evidence of deposits associated with these sediment sources to the river.

Slaking Tests

To explore the fate of colluvium in these two streams, we detached clasts of bank rock from many sites along both Pescadero and Butano Creeks, such as would be input into the creeks

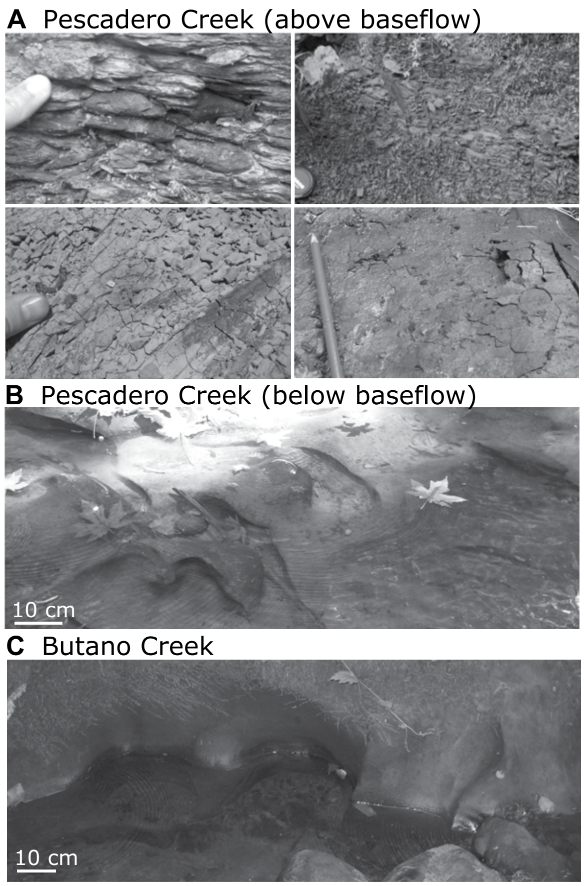

Figure 4. (A) Examples of bank rock textures in the Purisima Formation mudstone indicative of slaking in Pescadero Creek. (B) The same rock is massive and unfractured below base-flow water levels and shows signs of abrasion-dominated erosion. (C) Butano Creek's banks do not show signs of slaking even above base-flow water levels.

via mass wasting, and subjected them to wetting and drying in the laboratory. Wet and dry periods lasting 48 h each ensured full drying and rewetting. Clasts (including the always-wet control group) were weighed, and their grain size was recorded after each cycle in order to track progressive breakdown of the clasts from slaking.

RESULTS

Slaking Occurs Only in Pescadero Creek, and There Only at Cutbanks

Butano Sandstone and Purisima Formation mudstone both have tensile strengths of ~0.5 MPa before drying (Fig. 5A). However, after one wet and dry cycle, the sandstone maintains its original tensile strength, whereas the mudstone loses so much strength that it disintegrates under its own submerged weight (Fig. 5A, inset). Therefore, the Butano Sandstone has a high slake durability, while the Purisima Formation mudstone along the sinuous Pescadero Creek has very low slake durability. This contrast in slake durability corresponds with a large difference in the susceptibility to erosion by clear-water flows. In particular, in Pescadero Creek, erosion via hydraulic jet occurs where rock has been exposed to drying above base-flow water levels but not where it is perpetually wet at base-flow water levels (Fig. 5B). This shows that drying of the rock and slaking allow for clear-water erosion of Purisima Formation mudstone. In contrast to the slaking textures seen in the field above low water levels, below base-flow water level in Pescadero Creek, bedrock is not fractured. Instead, textures are massive and smooth with flutes and scour indicative of erosion by suspended-load and bed-load impact abrasion (Fig. 4B). In Butano Creek, bedrock textures are similar to those below Pescadero's base-flow water levels: massive and smooth with flutes and scour indicative of erosion by suspended-load and bed-load impact and abrasion, even above base-flow levels where bedrock dries seasonally (Fig. 4C). In Butano Creek, erosion was never possible with water jets (Fig. 5B) and taking bedrock samples was even difficult with a sledgehammer and pick. Because of these observations and the jet results, and because even fully exposed bedrock does not slake to form a rind of predetached bedrock, we assume that neither fluid shear stress nor the exposure of bedrock due to scour controls bedrock erosion in Butano Creek.

Detailed mapping in Pescadero Creek reveals a ubiquitous bar-slaking pattern at active meander bends (Figs. 6A and 6B). A curvature-forced point bar is always found on the inside of the bend (Ikeda, 1989). These bars are made of sand, gravel, or cobbles of durable rocks sourced from far upstream. If locally derived Purisima Formation mudstone is present on these bars above low flow water levels, it will always be fractured and disaggregated (Fig. 7C). On the bank opposite these bars, along the outside concave bank or "cutbank", bedrock is nearly always exposed and highly fractured in a pattern consistent with our criteria for identifying slaking (Fig. 4A). The steep hillslopes/cliffs above cutbanks, though above storm stages, also exhibited slaking textures, suggesting precipitation provides enough moisture for slaking. We observed that slaked rinds were removed by gravity on the steepest cliffs, but in other areas, landslides had exposed fresh bedrock to slaking. Fallen trees suggest rapid bank and hillslope retreat. No talus was found to last more than one dry-rewet cycle below these slopes. Instead, a narrow (~0.5–3-m-wide) bedrock bench was often found at the base-flow water level between the cut slope cliff and the deepest thalweg pool (Fig. 6B). Between bends, at curvature inflection points where the channel was close to straight, the thalweg was centered in the channel, and banks nearly always had vegetation and soil covering both banks down to base-flow water levels.

A commonly assumed mechanism for lateral bedrock bank erosion is undercutting of a bank

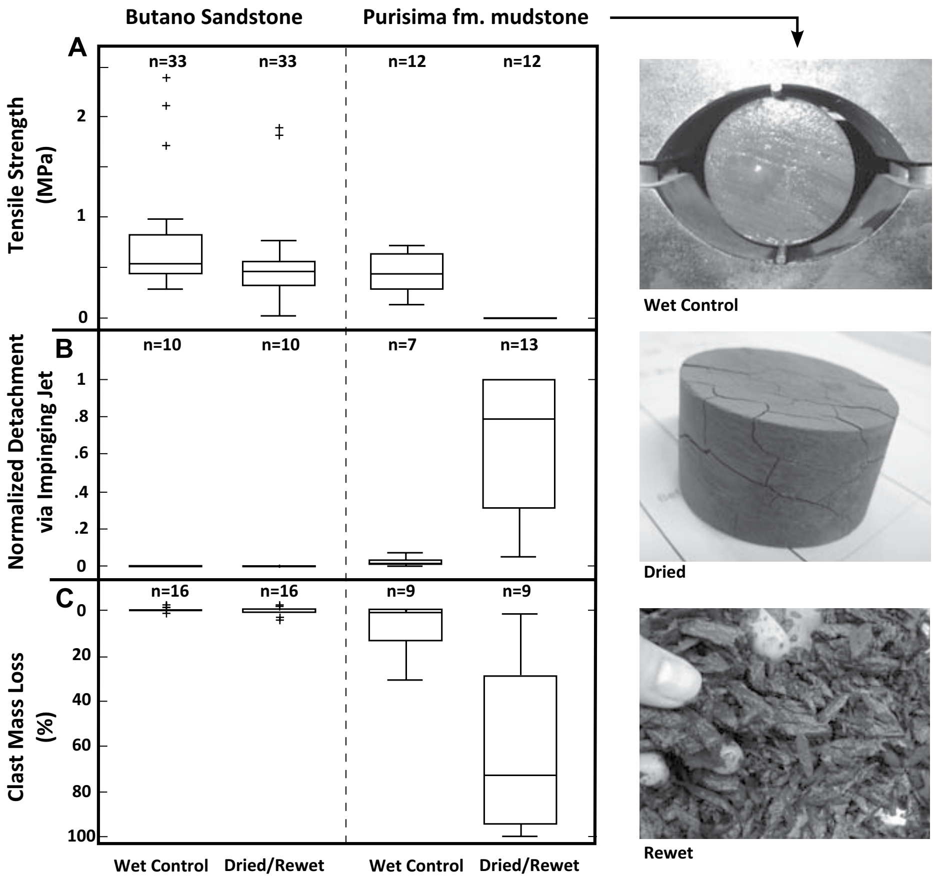

Figure 5. Rock strength tests for Butano Sandstone and Purisima Formation mudstone: box plots delineate the median and 25th and 75th percentiles. (A) Tensile strength was not significantly different among the Butano Sandstone control group, Butano Sandstone rewet group, and the Purisima Formation mudstone control group. Tensile strength measurements for the dried and rewet Purisima Formation mudstone, however, are zero because cores slaked dramatically and collapsed under their own weight (inset). (B) Results for erosion via clear-water jet followed the same pattern as tensile strength with significant erosion only possible for mudstone that had experienced drying. (C) Hand sample mass loss due to slaking was only significant for the mudstone from Pescadero Creek. Some mass loss occurred in the Purisima control group due to slight accidental drying in transport from the field; however, this was small compared to the signal between the control and treatment groups. Photos to right show the texture of our slaked rock is similar to textures seen in the field.

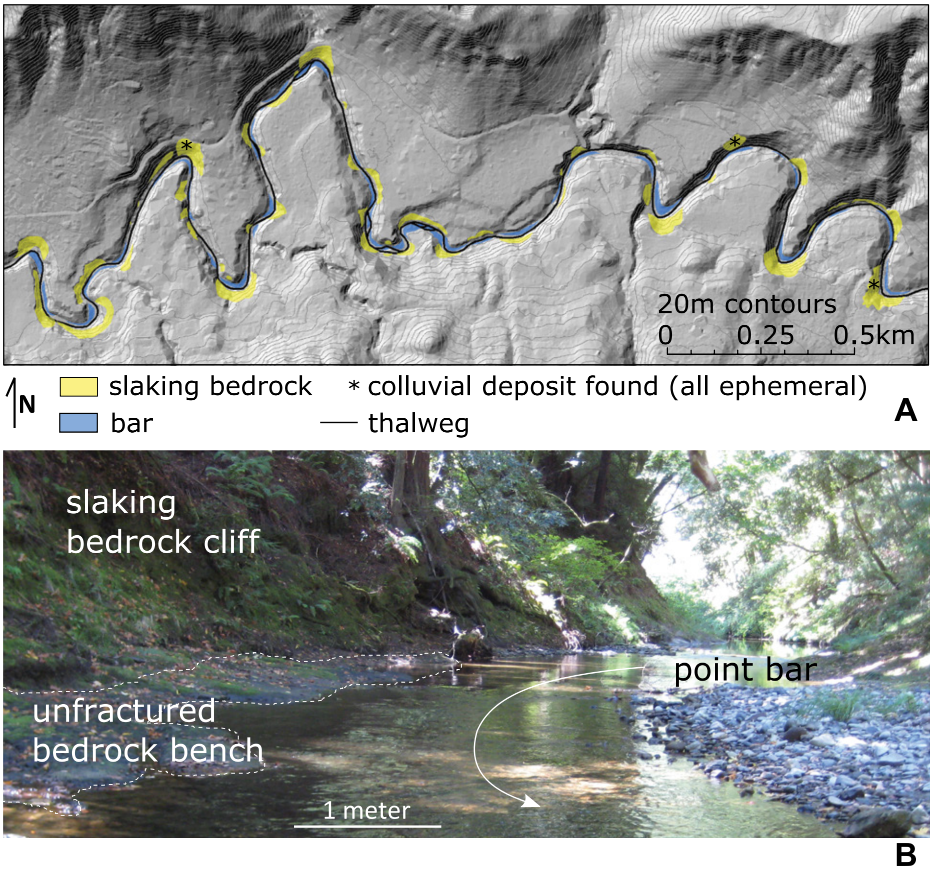

Figure 6. (A) Slaking erosion is ubiquitous along the bedrock cutbanks of meander bends and the steep cliffs above these banks, yet it is found nowhere else in the landscape (except steep road cuts). These steep cliffs above meander bend cutbanks are prone to mass wasting and slaking, yet persistent colluvium was never found below these sources. The arrows denote three places where ephemeral colluvial deposits were found but washed away in the next storm event. Bars form along the inside of all meander bends. (B) Example of the ubiquitous pattern at meander bends: an inside "point" bar and a slaking bedrock "cut slope." Note the bench of saturated bedrock along the outside of the bend.

by bed-load tools and subsequent bank collapse (Cook et al., 2014; Fuller, 2014). Although any mechanism where lateral bedrock erosion is spatially limited to high-curvature cutbanks could initially drive meandering, in-stream evidence in Pescadero Creek clearly counters the idea that bed-load undercutting is the primary driver of erosion at cutbanks. Instead of being undercut, cutbanks often had an elevated bedrock bench at the base-flow water level outboard of the thalweg (Fig. 6B). Bed-load "tools" were never found on these benches despite the fact that they were often close to flat, implying that if bed load were in these locations at high flows, some would become stranded on these surfaces. Bed load was clearly confined to the deeper thalweg trench inboard of the bench in these locations. Third, exposed dry bedrock showed clear signs of slaking erosion, not abrasion. So, lateral erosion in Pescadero Creek appears to not be dependent on bed-load tools, but instead on rock moisture history.

This pattern is always found in Pescadero Creek in active bends where the bend has a radius of curvature smaller than ~60 m or ~6 channel widths (Figs. 6A and 8). However, some parts of what might, on first observation, be considered a single meander bend do not show this pattern: In these cases, parts of the bend with tighter radii of curvature show this pattern, while lower-curvature reaches along the bend have banks that resemble between-bend straight reaches where banks have vegetation and soil down to at least base-flow water levels.

In situ rewetting of dried bedrock shows that slaking rinds on the order of 1–8 mm are detached with just still water after each drying cycle (Table 1). Presumably, fluid shear stress could increase the depth of detachment of slaked bedrock; however, this represents a minimum bound on erosion per drying cycle. These results demonstrate significant erosion that can occur on exposed bedrock in Pescadero Creek after each wet-dry cycle.

Slaking Prevents Accumulation of Talus in Pescadero Creek

Here, we present results from tests addressing the second challenge to meandering in bedrock systems: our hypothesis that colluvium can armor cutbanks and exert a negative feedback on lateral bank erosion, but that slaking prevents accumulation of talus. In Pescadero Creek, at the apex of meander bends when the thalweg is close to a valley wall, the bedrock cliff above the cutbank is consistently ~45° and usually ~30 m tall. Therefore, with every meter of lateral incision by the thalweg, on the order of 30 m^3 of colluvium will be deposited along that bank per meter of river channel length. Landslide and rockfall scarps attesting to the production of colluvium in Pescadero Creek were present at all of the mapped cutbanks (Fig. 6A), but colluvium was rarely found in association with these scarps. In fact, the only deposits found were either found just after a storm while still saturated, and were observed to slake upon drying (Fig. 7A), or where the deposit was bound together by vegetation that came down in a landslide (Fig. 7B).

Our laboratory tests showed that Pescadero's bedrock slakes dramatically when dried as a detached boulder or cobble, whereas Butano Sandstone (which does not slake) did not erode during drying and rewetting tests (Fig. 5C). Detached rock clasts dried and rewet in the laboratory showed similar fracture patterns as those observed in the field (Figs. 5 and 7C). Breakdown of the mudstone clasts was not gradual, but instead even large clasts were typically reduced to shards on the order of 2–10 mm diameter after one drying-rewetting cycle (Fig. 5C). This behavior is much more dramatic than the development of "slaking rinds" observed when bank rock dried in situ (e.g., Fig. 4A). This extreme slaking converted colluvium from grain sizes that would be persistent at high-flow conditions into grain sizes that could be transported during modest-flow conditions. When core samples (detached clasts) were tested without drying, their strength was comparable to that of Butano Sandstone (~0.5 MPa). However, after drying and rewetting, cores disintegrated to fine-grained sediment (Fig. 5A) and essentially had no tensile strength and therefore collapsed under their own submerged weight.

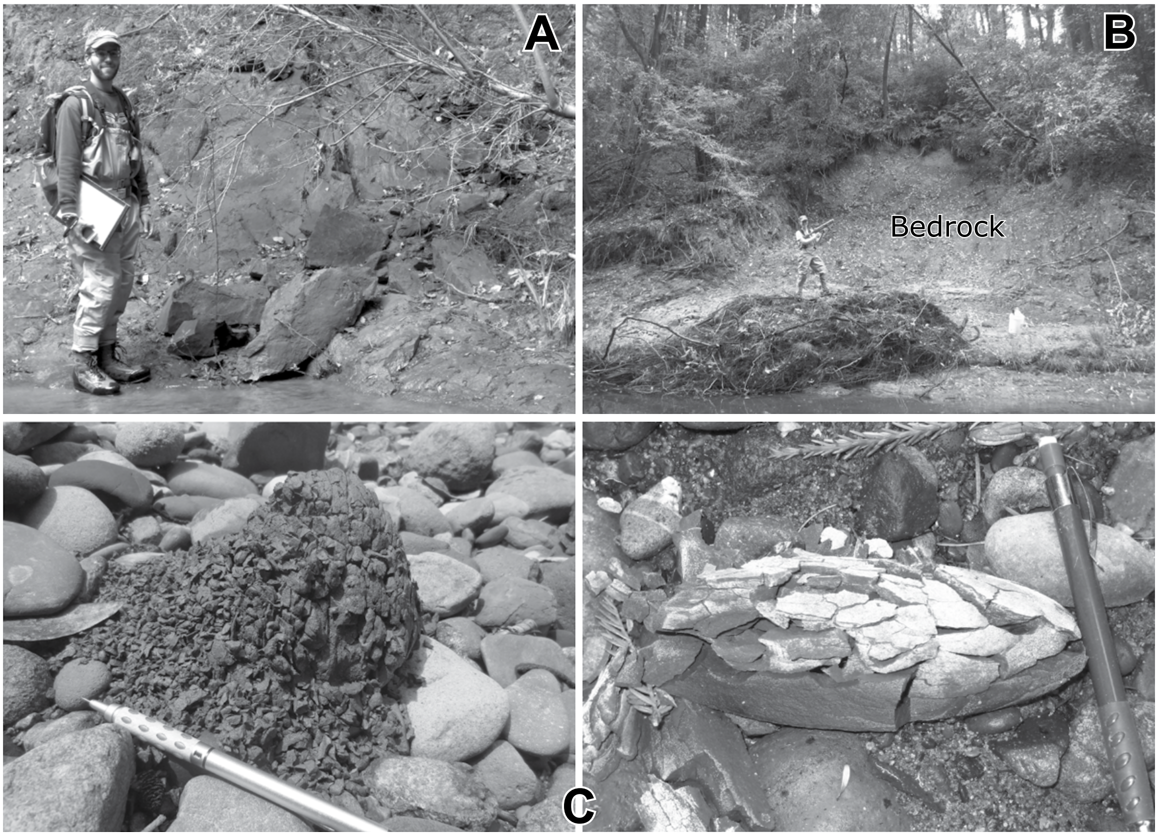

Figure 7. (A) Large-grain-size colluvium was only found immediately after a storm (i.e., detachment event) when rock had not yet dried. (B) Vegetation is all that is left of a recent mass-wasting deposit. Bedrock is exposed, and slaking is seen along scarp. (C) Mudstone clasts slake in place at low flow and are poised for transport during next high-flow event, yet they were strong enough to become rounded while kept wet within the river.

Locally derived Purisima Formation mudstone makes up some of Pescadero Creek's bed load and is competent enough to become rounded during transport, but if it is abandoned above base-flow water levels, it will slake to small shards (Fig. 7C) with similar textures and fracture patterns to those observed in our laboratory tests (Fig. 5). Therefore, most of the bed load in Pescadero Creek is made up of lithologies from upstream that do not slake (e.g., Fig. 7C, background).

In laboratory tests, Butano Sandstone remained intact without losing mass (Fig. 5C) or strength (Fig. 5A). In Pescadero Creek, slaking makes colluvium so readily transportable downstream that persistent talus piles, which would otherwise impede lateral channel migration and meandering, apparently do not form. Overall, these tests show that colluvium in Pescadero Creek does not persist to protect cutbanks from further erosion, while large-grain-size clasts of Butano Sandstone were commonly observed associated with landslides, debris flows, and in the channel (Fig. 9).

DISCUSSION

Conceptual Model for Slaking-Driven Bedrock Meandering

A conceptual model for slaking-driven bedrock meandering emerges from these results. In Pescadero Creek, slaking drives rapid bedrock bank erosion where bedrock is exposed to drying at the surface. Slaking erosion is localized along cutbanks at the apex of bends with a radius of curvature, nondimensionalized by channel width, of less than ~6. As is well studied in meandering alluvial rivers, curvature-induced changes in transport capacity of flow around bends force scour of alluvium at the cutbank and deposition at the point bar (Dietrich et al., 1979; Einstein, 1926; Ikeda et al., 1981; Leopold and Wolman, 1960). This change in transport capacity is inversely proportional to the radius of curvature of the bend, with tighter bends having higher divergence of stress and transport up to a point where a bend is so tight that the flow pattern breaks down (Harden, 1990; Hickin and Nanson, 1975). In Pescadero Creek, fluid scour along cutbanks in tight bedrock bends keeps bedrock free of soil and alluvium, and thus it is exposed to wetting and drying at the surface, causing slaking and rendering rock transportable at these locations. The fact that slaking bedrock is only found along convex parts of bends (typically with a radius of curvature of less than ~6 channel widths) supports the idea that bedrock meandering in Pescadero Creek is driven by curvature in a similar way to alluvial meandering. In further support of this model, we note that low-curvature banks, such as those on the flanks of bends and the inflection zones between bends, similarly never exhibited bedrock exposed to drying at the surface and were typically soil mantled down to the low water line. This suggests that bank shear stress is only high enough to expose bedrock and enable slaking at the outside of tight bends. The optimal curvature for meandering in alluvial rivers has been empirically shown to be ~3 channel widths (Hickin and Nanson, 1975; Hooke, 2003; Nanson and Hickin, 1983). The curvature

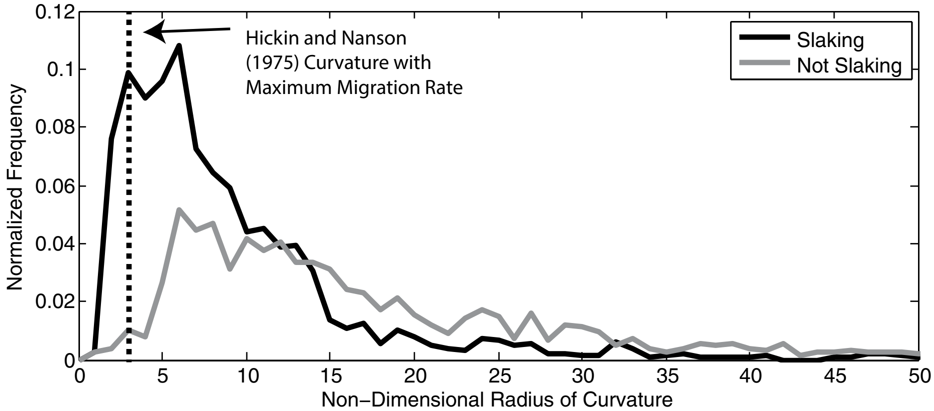

Figure 8. Locations along Pescadero Creek's bank that show signs of slaking have systematically tighter radius of curvature compared to locations along the banks that do not show signs of slaking. The peak frequency of slaking occurs at the same normalized radius of curvature (~3) shown to be optimal for lateral erosion in meandering alluvial rivers by Hickin and Nanson (1975). These curvature data are taken from points every 10 m along Pescadero Creek in the study section shown in Figure 6A and have been divided based on proximity to mapped slaking. Mapping showed that slaking does not occur if a bend does not reach a normalized radius of curvature lower than ~6, but these data incorporate the lower-curvature flanks of tighter bends where slaking may still occur.

of Pescadero's active bends clusters within this same range (Fig. 8). This supports our hypothesis that a bedrock river cutting rock with low slake durability can meander via the same general morphodynamics observed in alluvial rivers (Fig. 9A).

The relative decrease in shear stress along the inside of a bend is known to cause deposition of a forced "point" bar in alluvial rivers (Ikeda, 1989), and this is consistent with our observations of extensive point bars in Pescadero Creek. These bars grade into soil-mantled hillslopes without exposed bedrock or any signs of bedrock exposure or erosion (Fig. 9A). We propose that sediment deposited in bars along the insides of bends shields bedrock from slaking and prevents bank erosion in this direction and therefore prevents widening of the channel. Thus, following a pulse of vertical incision, sediment-covered bedrock will be abandoned above the active channel along the inside of a bend, thereby forming an unpaired strath terrace. Low-curvature banks, such as those on the flanks of bends and at the inflection zones between bends, similarly never exhibited bedrock exposed to slaking at the surface. However, at these locations, soil and tree roots, instead of bar deposits, protected banks from drying. Hence, the increase in transport capacity makes cutbanks uniquely subject to slaking and rapid bedrock erosion, while the lower-transport-capacity straight and convex banks are protected from rapid moisture fluctuations at the surface by soil and bars and do not slake or erode laterally (Fig. 9A).

TABLE 1. EROSION INTO BANK BEDROCK MEASURED AFTER ONE DRY-REWET CYCLE IN PESCADERO CREEK

Pescadero site no.	Linear erosion equivalent (mm)
1	3.5
2	7.7
3	8.1
4	4.9
5	1.2
6	3.2

Sustained lateral channel migration, however, is only possible if the large volume of bedrock that must be eroded from the valley wall for the channel to move laterally does not accumulate to form talus that protects the bank from further erosion. The oversteepened valley walls above cutbanks were observed to slake in place, presumably due to precipitation-driven moisture fluctuations, and to erode via landslides and rockfall. However, colluvium is not persistent in Pescadero Creek because material slaked from cliff faces is often fine grained, and because any large-grain-size colluvium is efficiently reduced to fine grain sizes upon drying (Figs. 7A and 7C). This slaked material is much finer than the channel's active bed load (Fig. 7C) and does not persist in even minor flow events, as evidenced by the lack of persistent colluvium in the channel even below landslides. In Butano Creek, large-grain-size colluvium was commonly observed in the channel (Fig. 10). Although, evidence for lateral incision was not observed in Butano Creek, talus would presumably form if valley walls were oversteepened, thereby causing a strong negative feedback on lateral bank erosion (Fig. 10A).

Efficient lateral erosion could be responsible for the presence of near-horizontal strath terraces on the inside of meander bends, which require lateral channel incision rates far in excess of vertical incision rates in order to form (Fig. 10A). In addition, the high efficiency of lateral erosion in bends is supported by our observation that up to 8 mm of bedrock slaking erosion can occur per drying cycle in the Purisima Formation in the absence of an applied fluid shear stress, whereas background erosion rates in the Santa Cruz Mountains are on the order of 0.1–0.6 mm/yr (Gudmundsdottir et al., 2013).

Generalization Beyond a Case Study

The new understanding of the meandering process we present for Pescadero Creek highlights lithology and rock mechanical properties as the first-order control on fluvial and valley-scale lateral incision. We show that in a slaking lithology, rock exposure and moisture history are key variables. High-sinuosity bedrock rivers with unpaired strath terraces and evidence for active meandering often occur in mudstones and sandstones that have very low slake durability (Arroyo Seco, California—Finnegan and Balco, 2013; South Fork Eel River, California—Fuller et al., 2009; Pancho Rico Creek, California—Garcia, 2006; Siwalik Hills, Nepal—Lavé and Avouac, 2000; Mendocino County, California—Merritts et al., 1994; Hsiukuluan River, Central Range, Taiwan—Shyu et al., 2006; Olympics, Washington, Cascades, Washington-Oregon, Oregon Coast Range, California, Coast Range, Taiwan—Stock et al., 2005). There may be other mechanisms that cause bedrock erosion along concave bedrock cutbanks and prevent talus from suppressing lateral bank erosion. However, in concert with the motivating common observation that bedrock river sinuosity correlates with lithology and often changes at lithologic boundaries, it follows that these mechanisms will also be lithology-specific. Therefore, understanding how climate and tectonic conditions interact with rock mechanical properties will likely be important in the interpretation of any strath terrace or sinuosity record.

Implications

Lateral Erosion and Channel/Network Mobility

This work proposes the first process-based conceptual model for active bedrock meandering. The existence of significant lateral channel mobility in bedrock channels opens the possi-

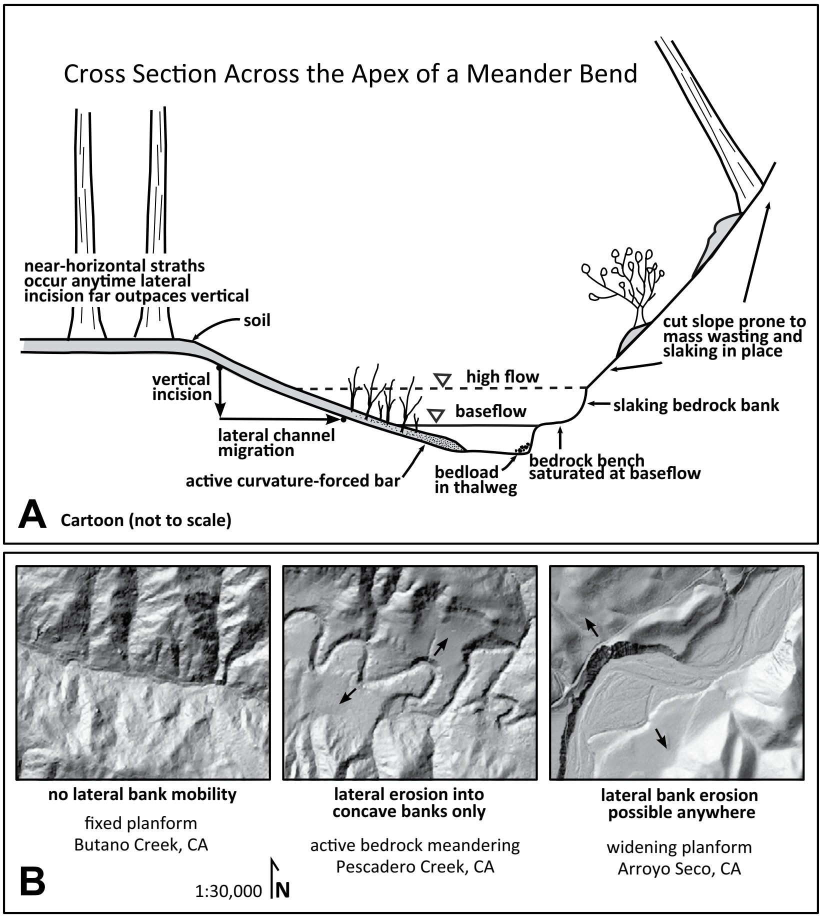

Figure 9. (A) Cartoon of a cross section across the apex of a typical meander left to right from the convex to concave bank. Soil and an active bar ensure that no bedrock is exposed on the convex side, while bedrock is exposed on the concave bank due to scour via an increase in transport capacity at the cutbank, and due to mass wasting and slaking on the oversteepened slope above the cutbank. (B) Meandering bedrock rivers occupy a unique niche between fixed-planform rivers with immobile bedrock banks, and rivers where slaking drives bank erosion everywhere above base-flow water levels resulting in channel/valley widening. A meandering river maintains a narrow channel while increasing the sinuosity of its planform because only concave bedrock banks are erodible.

bility for changes to the shape and arrangement of drainage networks that is triggered by lateral motion from trunk channels. Thus, the existence of laterally mobile trunk channels provides an explanation for drainage divide migration at the watershed scale (e.g., Willett et al., 2014).

Lateral and Vertical Incision Are Decoupled

Vertical fluvial bedrock erosion is thought to be dominated by abrasion wear in many settings (Sklar and Dietrich, 2004; Lamb et al., 2008). Therefore, the rate of vertical channel incision is controlled by factors such as discharge (including flood magnitude and duration), channel slope, sediment size and supply, bed exposure, and the mode of sediment transport. We have shown that the main control on lateral bank erosion in a low-slake-durability lithology is the number of wetting and drying cycles per year. Therefore, vertical and lateral incision may be poorly coupled in these systems. For example, two small precipitation events separated by a dry sunny day may cause twice the lateral incision yet barely initiate bed-load transport. We speculate that the width of the bedrock bench observed along the outside of bedrock bends reflects a condition in which lateral incision above base-flow water levels outpaces migration of the thalweg, where erosion is dominated by abrasion. How these apparently distinct mechanisms of erosion interact to maintain channels warrants future study.

End Members on Channel Width and Mobility

The ability to meander in rock while maintaining a constant-width channel requires lateral erosion of concave but not convex bedrock banks. If both banks erode, the bedrock channel/valley will not meander, instead it will widen and carve a strath (e.g., Montgomery, 2004; Stock et al., 2005), potentially resulting in alluvial braiding (e.g., Finnegan and Balco, 2013) or alluvial meandering (e.g., Dury, 1965) within the wider bedrock canyon. On the other hand, if lateral bank-rock erosion does not occur or is suppressed by persistent colluvial armor, the channel planform would remain fixed. Meandering bedrock canyons therefore represent a specific and unique intermediate condition between a fixed-location channel and a widening bedrock channel/strath, specifically, one where only concave banks undergo lateral erosion (Fig. 10B).

Strath Interpretation

Strath terraces are generally found in weak sedimentary rocks that are prone to slaking (Montgomery, 2004). Hence, this understanding built from Pescadero Creek may have implications for many other strath-forming rivers. Strath terrace formation is usually explored outside the context of bedrock meandering despite the fact that most unpaired strath terraces are found in meandering bedrock systems (Finnegan and Dietrich, 2011; Lavé and Avouac, 2000; Merritts et al., 1994; Personius et al., 1993; Shyu et al., 2006). In order to understand the record archived in any flight of strath terraces, the process of lateral bank erosion must be considered along with the processes of vertical incision. For example, along meandering rivers, the flight of terraces developed on the inside of a meander bend records the ratio of vertical to lateral incision of a meander bend provided that several terrace cycles have been integrated (Almond et al., 2007; Finnegan and Dietrich, 2011). Viewed in this context, a wide terrace tread could either represent a pause in vertical bedrock incision, or a period of increased lateral mobility. Hence, without an understanding of the specific factors that influence lateral erosion rates, or in this case, rates of channel meandering, it is difficult to interpret the significance (climatic, tectonic, or otherwise) of strath terraces.

Climate Signals

Given an understanding of the controls on lateral bank mobility, more pointed and focused questions can be asked about the ways in which climate affects the ratio of lateral to vertical channel incision as recorded in strath terraces. For example, we have shown here that exposure and drying of bedrock at the surface are key factors to lateral erosion in Pescadero

Figure 10. Butano Sandstone holds large grain sizes in Butano Creek.

Creek. Therefore, changes to aspects of climate that effect surface moisture should in turn have strong effects on lateral erosion. Specifically, Pescadero Creek is in a xeric climate with consistently dry summers and short, concentrated winter precipitation (generally due to cold fronts) punctuated by dry periods. A shift to more consistent and evenly distributed precipitation might limit lateral bank mobility in Pescadero Creek by reducing the number of wet-dry cycles per year, or it could increase the number of wet/dry cycles if summer storms occurred. An example of a climatic change that would likely affect Pescadero Creek's lateral incision rates and the spatial pattern of lateral incision via this conceptual model would be the loss of summer fog. The redwood forest that shades the banks of Pescadero Creek is adapted to summer fog and relies on fog drip precipitation to make it through the otherwise dry summers (Dawson, 1998). Fog provides both a source of summer soil moisture and shade. Our conceptual model of bedrock meandering in a slaking lithology would predict that a loss of summer soil moisture and shade would make slaking of convex and low-curvature banks more likely. This, in turn, could lead to erosion of bedrock banks on both sides of a channel and result in channel widening and planation of a strath. It is not yet clear how climate change will affect coastal fog in California (O'Brien et al., 2013); however, a decline has been observed over the last hundred years (Johnstone and Dawson, 2010). Armed with this type of process-based understanding of how the lithologic response to bedrock moisture drives active bedrock meandering in watersheds like Pescadero Creek, we can better explore the climatic controls on strath terrace records.

CONCLUSION

Here, we have explored a natural experiment in the Santa Cruz Mountains, California, where the main difference between an actively meandering bedrock stream (Pescadero Creek) and its adjacent straight neighbor (Butano Creek) is lithology. We find that landscapes underlain by lithologies with a low slake durability are uniquely predisposed to bedrock meandering and strath terrace formation.

On a process scale, this meandering occurs due to the same fluid dynamics as meandering alluvial rivers: Elevated transport capacity at the cutbank of meander bends strips alluvium, protective soil, and vegetation from the cutbank, but, in this case, erosion occurs because this exposes bank rock to drying. For a slaking lithology, exposure to drying (with rewetting opportunities at high-flow stage and with precipitation above the active channel) makes erosion at cutbanks very efficient even without bed-load tools. We propose that in most settings, lateral channel migration would be suppressed by the colluvial armor/talus that would result from a channel cutting laterally into a bedrock valley wall. However, Pescadero Creek's mudstone bedrock disintegrates within one drying and rewetting cycle, preventing buildup of persistent talus. In these two ways, slaking provides a much more efficient erosion mechanism for cutbanks of the meandering bedrock river than background landscape erosion rates.

We show that in slaking lithologies, lateral erosion is controlled by different drivers than vertical incision, leaving these processes poorly coupled. Understanding the mechanism for active bedrock meandering, lateral channel migration, and bank erosion in general is crucial for interpreting strath terrace records as well as the planform shape of bedrock river networks themselves.

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