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OBSERVATIONS ON THE ROLE OF LITHOLOGY IN STRATH TERRACE FORMATION AND BEDROCK CHANNEL WIDTH

DAVID R. MONTGOMERY

Quaternary Research Center and Department of Earth and Space Sciences, 19 Johnson Hall, Campus Box 351360, University of Washington, Seattle, Washington 98195-1360, USA: dave@ess.washington.edu

ABSTRACT. Field observations from western Washington and eastern Tibet indicate a strong lithologic influence on strath terrace formation and highlight the response of bedrock channel width to spatial gradients in bedrock erodibility and/or rock uplift rates. Measurements of local bedrock bed and bank erosion rates together with observations of the role of weathering processes on erosion of siltstones and sandstones illustrate a mechanism that underlies a conceptual model that predicts a strong lithological control on strath terrace formation. Direct measurements of bedrock erosion rates in lithologies susceptible to accelerated erosion upon sub-aerial exposure show that lateral rates of bedrock bank erosion can substantially exceed vertical incision below the perennial flow level due to an asymmetry in erodibility between perennially submerged rock and rock exposed to cyclic wetting and drying on bedrock channel walls. Under such conditions, the rapid, weathering-mediated lowering of bedrock exposed above baseflow promotes development of a beveled bedrock platform that could become a strath terrace upon abandonment. In contrast to previous studies, channel widths measured across a substantial gradient in lithology, slope, and long-term erosion rates in eastern Tibet do not follow conventional relations where channel width scales as a power law function of drainage area. Instead, as they flow across a zone of rapid uplift these channels systematically narrow relative to the predicted width extrapolated from traditional power-law relations. Field studies from a wide range of geological settings and lithologies support the interpretation that, in general, strath terraces tend to be more extensive in rivers flowing over weak sedimentary rock and tend to be poorly developed and/or preserved where rivers flow over hard, erosion-resistant rock.

INTRODUCTION

Models of the processes governing the formation of erosional, bedrock-cored river terraces—known since the 1930s as strath terraces (Bucher, 1932)—are not as well established as models of processes responsible for the formation of constructional alluvial river terraces. Various conceptual and numerical models of strath terrace development predict that they form in response to periods of balanced sediment supply (Formento-Trigilio and others, 2003), altered sediment supply (Pazzaglia and Brandon, 2000; Wegmann and Pazzaglia, 2002), oscillating sediment supply (Hancock and Anderson, 2002), tectonically induced changes in local rock uplift (Rockwell and others, 1984; Molnar and others, 1994; Mukul, 1999), falling local base level (Born and Ritter, 1970; Reneau, 2000), eustatic sea level fall (Pazzaglia and Gardner, 1993; Merrits and others, 1994), or autocyclic oscillations in erosion rate in laterally migrating channels (Hasbargen and Paola, 2000).

Progress continues in unravelling the conditions under which strath terraces form, and it is likely that there are multiple ways to form them. Increasingly, field studies in tectonic geomorphology use strath terraces to discern rates of bedrock river incision (for example, Burbank and others, 1996; Leland and others, 1998; Reneau, 2000; Barnard and others, 2001; Hsieh and Kneupfer, 2001; Pazzaglia and Brandon, 2001; Wegmann and Pazzaglia, 2002), and an understanding of both the mechanisms and timing of strath terrace formation and abandonment is essential for understanding landscape evolution. By whatever mechanism, formation of wide valley bottoms underlain by beveled bedrock surfaces requires an interval of time wherein lateral erosion of bedrock channel banks or valley walls exceeds the vertical rate of bedrock incision. In addition, the formation of strath terraces (fig. 1) requires a subsequent period of accelerated channel incision and floodplain abandonment. Recognizing that different mechanisms of strath terrace formation are likely to be more (or less) important in different geological settings, this paper addresses conditions favoring the development of extensive, well-defined strath terraces based on observations synthesized from experiences working in bedrock rivers in mountain drainage basins of western North America and eastern Tibet.

SUB-AERIAL WEATHERING AS A CONTRIBUTING MECHANISM FOR STRATH TERRACE FORMATION

The propensity for rapid weathering and erosion of marine sedimentary rocks subaerially exposed in channels of the coastal mountains of western North America is readily attested to by piles of sand formed from gravel clasts exposed to wetting and drying on gravel bars (fig. 2A). Throughout the region, late Tertiary micaceous marine sandstones and siltstones rapidly break down into fine sediment readily transported by even modest flows. Stock and others (2005) found that exposure to cyclic wetting and drying of bedrock channel beds carved into marine sandstone and siltstone caused erosion at rates more than two orders of magnitude greater than long-term rates. Based on erosion pin studies at six sites in a wide range of settings, Stock and others (2005) further found that where these same rocks were exposed in the perennially wetted thalweg they eroded at far slower rates closer to the long-term average. Similarities among observations collected during repeated visits to two of these sites, the West Fork Satsop and Teanaway rivers, provide the foundation for a conceptual model wherein weathering-driven bedrock erosion promotes the development of wide floodplains, and therefore the potential for strath terrace formation in lithologies susceptible to rapid mechanical breakdown upon sub-aerial exposure.

Formation of wide floodplains requires erosion of bedrock valley walls at rates faster than the rate of bedrock lowering in the channel. The role of subaerial weathering in promoting rapid lateral bedrock erosion, and thereby the formation of bedrock-cored floodplains, may be important because it is clear that in many cases even large rivers lack significant capacity to erode intact bedrock banks, as illustrated by deeply entrenched, vertical walled river meanders in the American Southwest (as illustrated, for example, by Leopold and Bull, 1979). In poorly indurated sedimentary rocks exposed along the West Fork Satsop and Teanaway rivers, rapid subaerial weathering of near-vertical banks together with greater bedrock competence when wet create an asymmetry in bedrock erodibility that provides the potential for rapid floodplain widening and a mechanistic link between channel widening, the generation of bedrock-cored floodplains, and strath terrace formation.

Satsop River

Observations from bedrock reaches of the West Fork Satsop River and its tributary Black Creek illustrate the manner in which wetting and drying processes promote the development of strath terraces in poorly-cemented sandstones. The West Fork Satsop River originates in Eocene basalts and flows into lowlands of Eocene through Miocene marine sedimentary rocks that unconformably overlie the basalt (Tabor and Cady, 1978). Montgomery and others (1996) mapped the extent of bedrock channels in Black Creek in 1995, when the channel had extensive reaches of alluvial cover impounded upstream of remnant old-growth logjams, and re-mapped the channel of Black Creek after a dam-break flood in 1996-1997 scoured the channel to bedrock over most of its length (Montgomery and others, 2003). Reconnaissance mapping associated with these field campaigns along the West Fork Satsop River indicated that strath terraces are common along channels in the sandstone and siltstone units, but are rare in reaches flowing over basalt in the upper portions of the drainage basin. While the

Fig. 1. Strath terraces cut into sedimentary rocks along (A) the Nenana River, Alaska, and (B) the West Fork Satsop River, Washington.

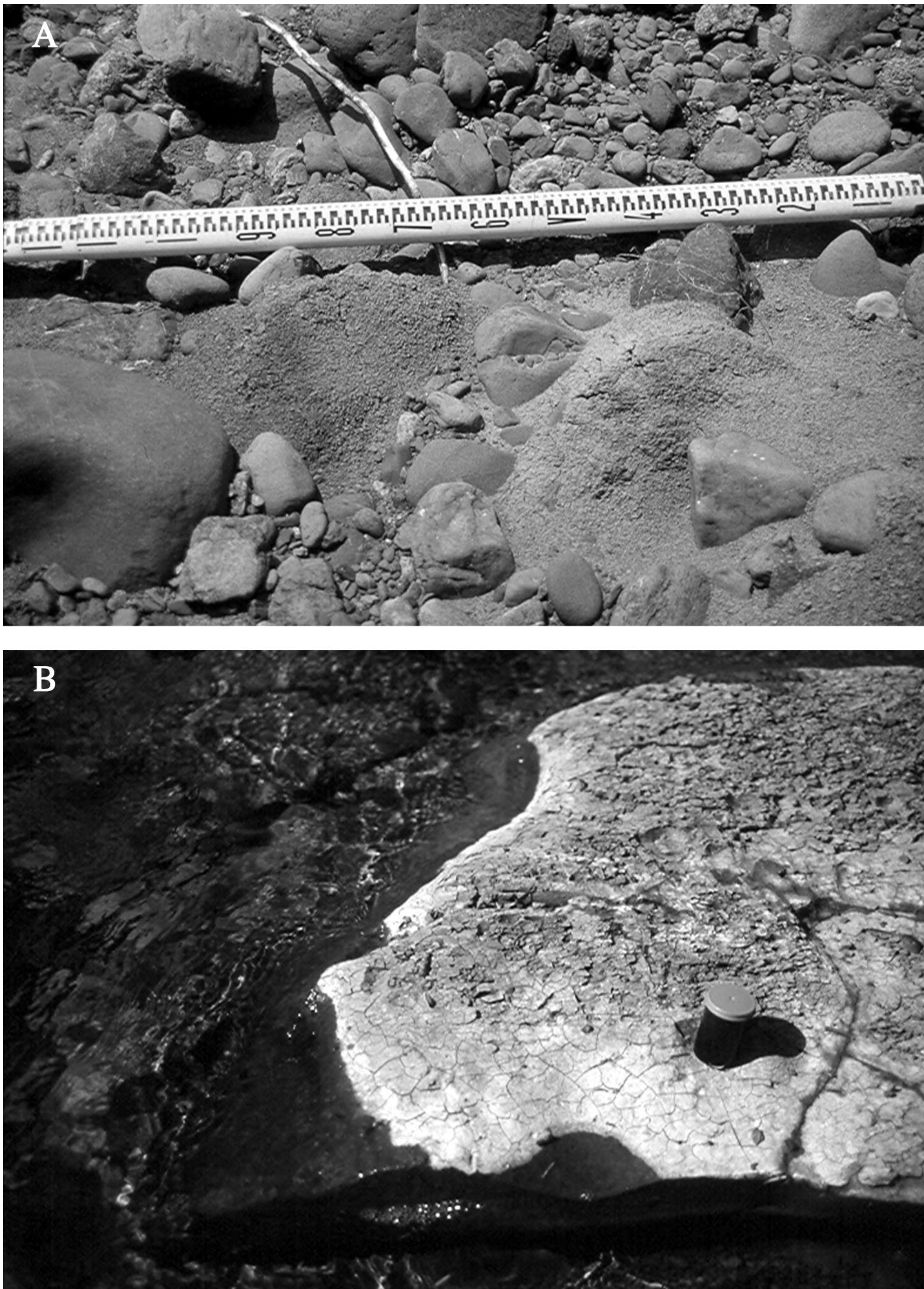

Fig. 2. Examples of the rapid sub-aerial weathering of marine sedimentary rocks. (A) Disintegrated cobbles along the West Fork Satsop River, Washington; (B) example of surficial weathering crust developed on sub-aerially exposed siltstone—note that submerged rock is intact.

distribution of strath terraces could reflect the delivery of a supply of coarse, durable basalt clasts to the lower reaches, or perhaps an influence of basin size on sediment supply, the relatively bare, exposed bedrock channel bed in the lower reaches points instead toward a lithologic effect.

Monitoring of erosion pins installed at sites on Black Creek and the West Fork Satsop River reveal rapid lowering of the portion of the bedrock channel bed that was exposed above summer low flows, and much slower bedrock erosion rates in the perennially submerged channel thalweg (Stock and others, 2005). Stock and others (2005) describe fully the methods employed in erosion pin installation and monitoring. Erosion pins installed on channel-spanning cross-sections at the West Fork Satsop site documented median annual rates of local bedrock surface lowering of 41 mm yr^{-1} in 1995-1996 and $>$130 mm yr^{-1} in 1996-1997. A similar array of erosion pins documented annual rates of 19 mm yr^{-1} and 40 mm yr^{-1} for the same periods at Black Creek. As discussed by Stock and others (2005), the greater rates in the second year of observations coincided with a dam break flood in the winter of 1996. Although the channel bed entrenched faster in the year of the dam-break flood, extreme discharges are not necessary for rapid incision of the channel bed as 1995-1996 was an unremarkable hydrologic year. Median lowering on Black Creek was 4 times greater in the zone above base flow than below it (fig. 3), although much of the channel bed dries during late summer months so even the thalweg is susceptible to desiccation and slaking. There was an even greater contrast in the lowering rate of sub-aerially exposed and submerged bedrock at the West Fork Satsop site, where the thalweg remains inundated throughout the year and lowering rates declined sharply to less than 1 mm yr^{-1} below the low-flow waterline, rates much closer to the long-term average lowering rate of about 0.3 mm yr^{-1} (Brandon and others, 1998).

In the field, it is readily apparent that the greater lowering rates where the bedrock channel bed is sub-aerially exposed during the summer dry season are controlled by the intense fracturing of the surficial layer of any rock extending above the waterline (fig. 2B). In contrast, the exposed bedrock is relatively intact and hard below the level of perennial flow, where measured lowering rates are much closer to long-term rates. A particularly dramatic illustration of the effect of wetting and drying on the comminution of the bedrock at this site is that within months of their collection intact boulders taken from below the waterline and brought back to the lab break into pervasively fractured pebble-sized clasts that would be reduced rapidly to the size of the constituent grains once re-entrained in the river. Many disintegrated clasts litter the surface of gravel bars in the late summer low-flow period when large areas of channel bed dry out upon emerging from the flow. Similar behavior characterizes sub-aerially exposed portions of the bedrock channel bed in which pervasive fractures cut across bedding and regional joint sets but parallel the local free surface.

The micaceous rocks at our study sites weather rapidly during sub-aerial wetting and drying, most likely when volumetric changes in the clay minerals exceed the cohesion of the rock, thereby breaking it up (Fujiwara, 1970; Mugridge and Young, 1983; Day, 1994). Over the low-flow season a thin blanket of loose material forms on the exposed channel bed. Consequently, rock exposed above the water line annually sheds a thin skin of friable exfoliated material up to several centimeters thick, much of which could be swept away with a broom. In contrast, fresh bedrock (that is, indurated medium-grained, micaceous sandstone and siltstone) exposed in the wetted riverbed is difficult to dislodge with a rock hammer. The surficial weathering process that converts intact bedrock to centimeter scale layers easily removed by even modest flows leads to rapid lowering of bedrock exposed above the low-flow channel.

Correspondence between the thickness of the weathering rinds and the annual bedrock incision rates measured at these sites implies that the process described above

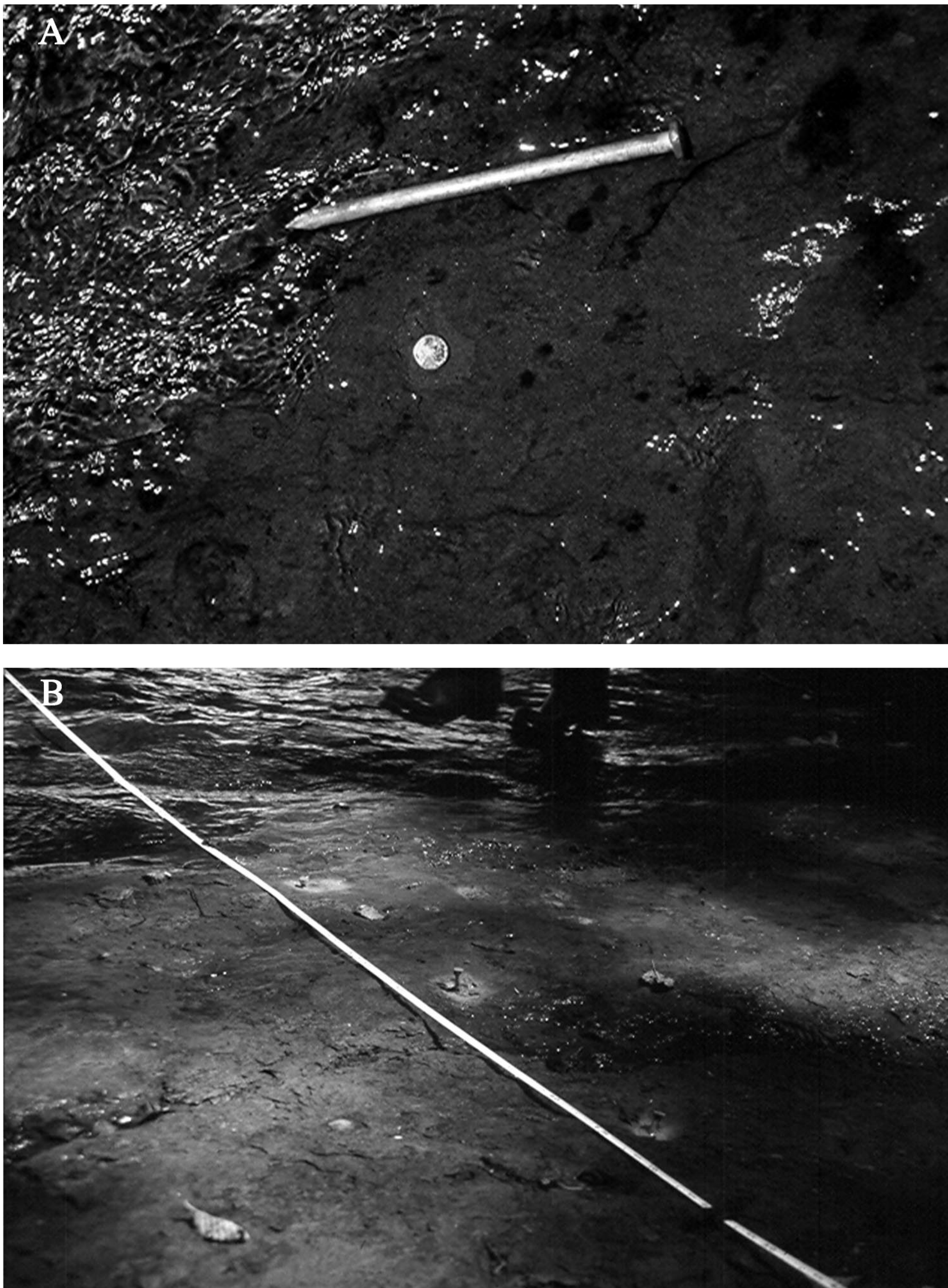

Fig. 3. Typical examples of contrasting rates of bedrock incision at Black Creek: (A) nails driven into portions of the bed that remained submerged year round exhibited little to no discernible incision, whereas (B) nails driven into sub-aerially exposed portions of the bedrock channel bed lowered rapidly.

controls local erosion rates on areas of exposed bedrock on both the channel bed and valley wall. The mean weathering rind thickness of 14 mm measured on the exposed bedrock valley wall (n=106) was close to the mean weathering rind thickness of 10 mm measured on the subaerially exposed bedrock channel bed (n=104) (figs. 4 and 5). No weathering rind was present on the bedrock exposed in the channel bed below the water level. At Black Creek the mean thickness of the combined set of 210 of these weathering rinds was 12 mm. The thickness of these weathering rinds was comparable to the annual bedrock lowering rates recorded on sub-aerially exposed portions of the bedrock bed of Black Creek (Stock and others, 2005), suggesting that annual lowering rates are set by the annual weathering rind formation and that a primary erosional role of high flows is to simply remove the weathered material. In this case, the annual high flow magnitude would not necessarily correlate with annual variability in erosion rates.

At our study site on the West Fork Satsop River a recently active and now abandoned strath terrace and a lower level beveled bedrock surface presently forming at the current high water mark illustrate how the rapid erosion of sub-aerially exposed sedimentary rocks can lead to formation of a beveled bedrock surface necessary to form a strath terrace. The site on the West Fork Satsop River is in a mixed alluvial and bedrock reach cut in poorly cemented Eocene sandstone and siltstone. A v-shaped low-flow channel is entrenched about 1 meter deep into a bedrock bench exposed on both sides of the channel during base flow (fig. 6A). Cut wood fragments found in alluvial deposits on top of a beveled bedrock surface 1.2 meters above this newly forming bench indicate historic abandonment of an approximately 100-m-wide bedrock-cored surface now covered by about 1 m of alluvium and some remnant log jams. The valley bottom at the site on the West Fork Satsop River consists of a mozaic of low-gradient channels now overgrown with 40 to 50 year old alder and higher surfaces upon which cedar and fir grow and where old growth stumps occur. The historical age of the alluvial deposits on top of the strath surface indicate that the present strath was an active floodplain during early post-European contact years, and probably until logging in the 1940s to 1950s.

The contemporary bedrock incision rate of centimeters per year in locations above the low-flow water level at the West Fork Satsop River site greatly exceeds any documented rock uplift rate, and is orders of magnitude greater than long-term erosion rates of $\sim$0.3 mm yr^{-1} indicated by apatite fission-track data from the southern Olympic Peninsula (Brandon and others, 1998). Alluvial deposits on 0.4 and 5 meter high strath terraces near the Black Creek site respectively contain detrital charcoal dated to 1290 +/- 100 yr BP and 7400 +/- 50 yr BP. The bedrock incision rates of 0.3 to 0.7 mm yr^{-1} recorded by these strath terraces are consistent with apatite fission track exhumation rates, but are far slower than the lowering of sub-aerially exposed bedrock currently ongoing above the waterline.

Teanaway River

A similar process of rapid bedrock lowering and formation of a beveled bedrock bench also is occurring on the Teanaway River on the eastern flank of the Cascade Range. The West Fork Teanaway River heads in glaciated Eocene sandstones of the Swauk Formation near the crest of the Washington Cascades and flows downstream through middle Eocene basaltic, andesitic and rhyolitic rocks of the Teanaway Formation (Tabor and others, 2000). Steep terrain associated with these rocks stops at a lithologic boundary with overlying micaceous Eocene sandstones and siltstones of the Roslyn Formation, into which the river has cut a wide, low-relief valley with multiple strath terraces. Just as in the case of the West Fork Satsop River, well-developed strath terraces with extensive beveled bedrock surfaces characterize reaches flowing through sandstone and siltstone, whereas reaches flowing through basalt are confined within narrow gorges lacking straths.

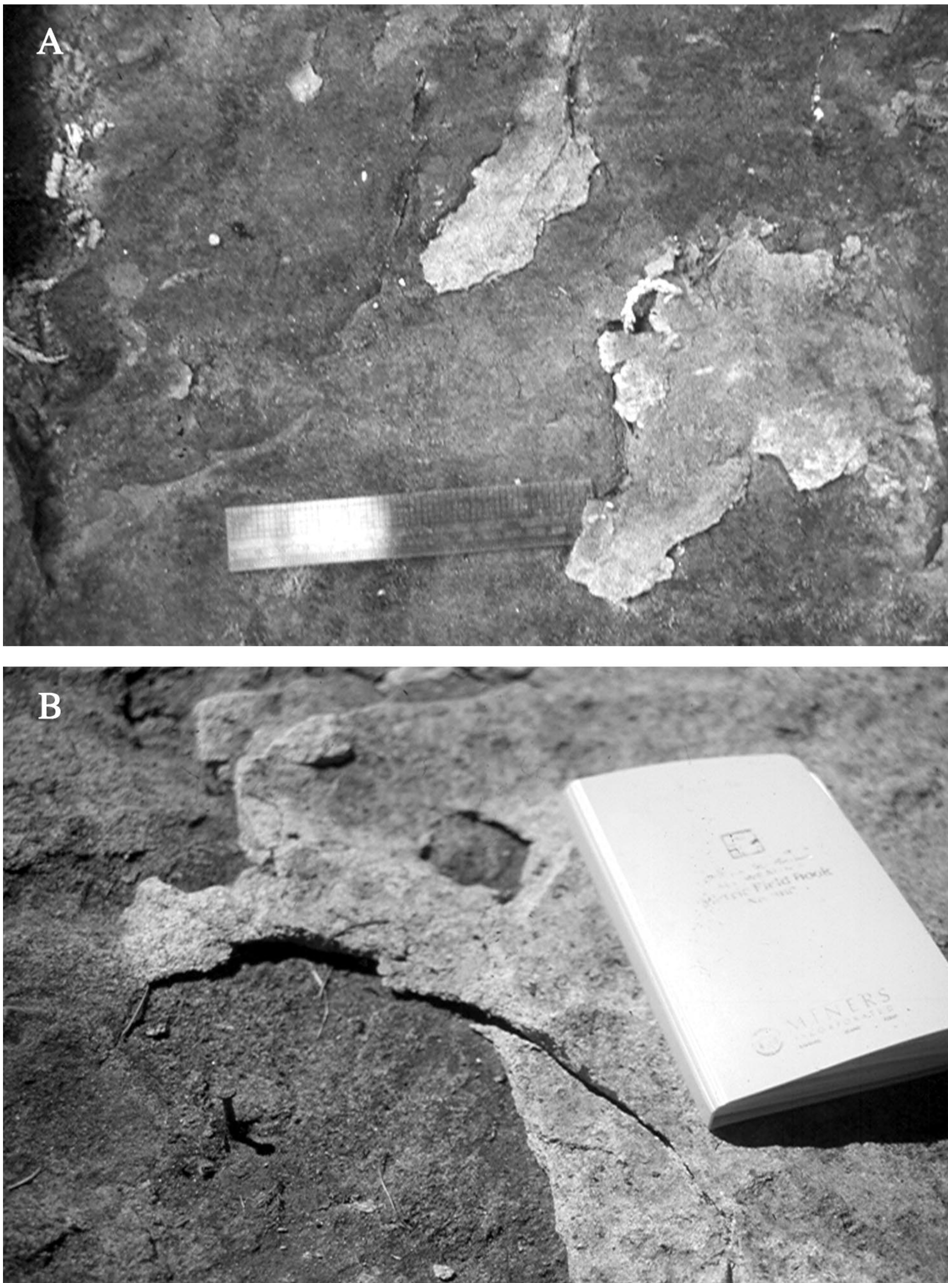

Fig. 4. Examples of exfoliation sheets developed on (A) valley wall and (B) bedrock channel bed of Black Creek.

The medium- to fine-grained, micaceous, lithofeldspathic sandstones of the Roslyn Formation exposed along the lower reaches of the West Fork Teanaway River have weathering features like those observed on Black Creek and the West Fork Satsop

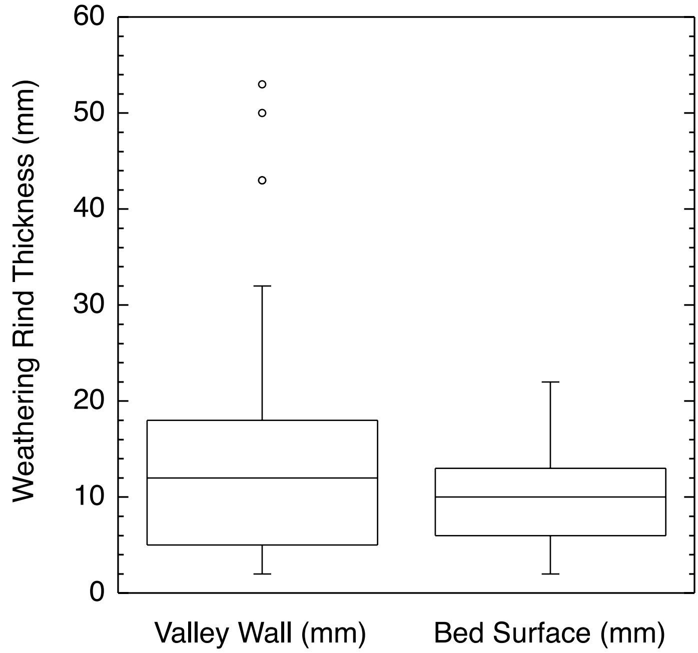

Fig. 5. Box and whiskers plot of the weathering rind thickness for bedrock exposed on the valley wall and in the subaerially exposed channel bed of Black Creek. Boxes define median and inner and outer quartiles, whiskers define 10^{th} and 90^{th} percentiles, and circles represent individual outliers.

River. By the end of the summer dry season, much of the beveled bedrock surface exposed above baseflow consists of a crust of weathered flakes ~0.01 to 0.1 meters thick (fig. 6B). Monitoring of three cross-sections of erosion pins revealed bedrock lowering rates similar to those recorded on the West Fork Satsop River and Black Creek (Stock and others, 2005). Whereas local bedrock lowering rates were rapid (mm yr^{-1} to cm yr^{-1}) where the channel bed dried during the summer, local bedrock lowering was not readily detectable (< 1 mm yr^{-1}) in locations where the channel bed remained submerged during low flow. Weathering rinds at the West Fork Teanaway River study sites were also millimeters to centimeters thick, revealing the potential for lowering rates far greater than the long-term erosion rates of < 0.1 mm yr^{-1} for the area (Reiners and others, 2002).

Monitoring of valley wall erosion rates at two sites on the West Fork Teanaway River indicate that they are also about a centimeter per year. At these sites, rapid valley wall erosion is beveling off a broad shelf at the low-flow water line and is creating a surface that could become a strath terrace if abandoned in the future. Over the course of almost four years of monitoring, erosion of the bedrock channel bank was sustained at about the rate of rind formation. Data from the first year of monitoring is reported in Stock and others (2005) and additional details of the monitoring of this site will be given elsewhere. Average bedrock bank erosion rates in the upstream site for the three and a half year period between November 2000 and April 2004 had an average rate of 8 ± 5 mm yr^{-1} ($n = 47$) for the pins installed in the bedrock channel bank above the seasonal low flow level. The mean rate for the downstream site, where most of the nails were eroded out and only six remained in place in April 2004, was 19.5 ± 4.5 mm yr^{-1} ($n=29$) for November 2000 and April 2004. The mean rate of bedrock bank erosion for the composite data set of 76 erosion pins installed at both transects for this period

Fig. 6. New beveled bedrock surfaces forming at about the low flow water level along (A) the West Fork Satsop River, and (B) the Teanaway River.

was 12 $\pm$ 8 mm yr^{-1}. Hence the average rate of bedrock bank erosion, and therefore the potential for valley wall retreat by this mechanism, is on the order of 1 to 2 centimeters per year.

Conceptual Model

At these study sites, different processes control erosion of bedrock above and below the low-flow water line. In the weathering-limited erosional system above the water line, the rate limiting factor in bedrock lowering is the frequency and penetration depth of the processes controlling the formation of a weathering rind. In contrast, the hard indurated rocks exposed below the perennial flow level appear to be lowered by more conventional processes of bedrock incision, such as by plucking or abrasion controlled by the erosive capacity of the flow as described by Whipple and others (2000a).

The dramatically greater bedrock erosion rates measured above the water line indicate that when bedrock susceptible to slaking is exposed to cyclic drying and submersion it will erode rapidly until it reaches the low-flow water level, at which point more conventional bedrock incision processes will lower the bed at a far slower rate. Such profound differences in erosion rates and processes above and below the low-flow water level indicate that a channel cut into rocks subject to slaking could more readily widen its valley than incise its bed. Hence, accelerated weathering above the low-flow stage would promote the formation of a wide beveled bedrock bench at or near the elevation of the thalweg due to an asymmetry in bedrock erodibility between incision of the wet channel bed and lateral erosion of seasonally desiccated bedrock banks.

The stark difference between the short and long-term rates of river incision can be reconciled if the bedrock channel bed spends most of the time buried under alluvium. Montgomery and others (1996) showed that local bedload storage associated with old-growth log jams could cover bedrock channel beds with an alluvial cover. The presence of large numbers of long-lived log jams would significantly retard river incision and the presence of extensive bed cover for much of the Holocene likely explains the apparent discrepancy between observed rates of river incision and the long-term incision rates apparent from the age-elevation relationships for strath terraces. It appears impossible to sustain for long the bedrock erosion rates that these channels are capable of if they are exposed to annual wetting and drying. Moreover, if the banks can erode as fast as the channel bed — as demonstrated here — then the channel cannot be effectively confined by narrow bedrock walls for long, since the channel will widen rapidly. In the absence of alluvium to form a channel bank, this would eventually expose the bed to seasonal desiccation and re-initiate rapid incision and further channel widening.

As such a bedrock channel widens, the bed will become progressively more exposed for longer durations during the low-flow season than if the flow was confined to a narrow channel. Hence, if the position of the thalweg can shift around the channel bed, as would be expected in the case of a bed with low-relief, then this should cause the channel to further incise and widen. But if enough sediment is available to build a floodplain on top of the exposed rock, then the channel can keep moving across the valley bottom contained between alluvial banks. This process may help explain why a period of aggradation is needed to help form straths because in the absence of any bed cover the channel may just continue to widen and deepen. Hence, the formation of at least one alluvial bank may be instrumental in sustaining strath terrace formation. It is probably no coincidence that most strath terraces are covered by a half a meter to several meters of gravel.

Variability of Bedrock Channel Width in Eastern Tibet

As discussed by Whipple and Tucker (1999), many landscape evolution models incorporate assumptions about how bedrock channel geometry scales with basin size into studies of landscape evolution that link fluvial geomorphology and tectonic processes. Because substantial local variations in channel width and unit stream power occur along bedrock channels (Wohl, 1992) it is not clear to what degree conventional hydraulic geometry relationships hold in mountain channel networks (Tinkler and Wohl, 1998). Classic hydraulic geometry relations show that channel width generally varies as a function of downstream changes in discharge wherein $w = cQ^b$ and where c and b are empirically determined. Assuming a similar form for the relation between discharge and drainage area allows recasting channel width in terms of drainage area as $w = cA^b$, where the coefficient c and exponent b need not be identical for discharge- or area-based scaling of channel width.

Relations with this general form have been found in classic studies of alluvial channels (Lacy, 1929; Schoklitch, 1937; Leopold and Maddock, 1953; Wolman, 1955; Leopold and Miller, 1956) and in more recent studies of bedrock channels (Montgomery and Gran, 2001; Snyder and others, 2001, 2003; Whipple, 2004). In a review of the literature on alluvial channels, Knighton (1998) concluded that the accumulated data "support the oft-quoted opinion that width varies approximately as the square root of discharge" (Knighton, 1998, p. 171). Montgomery and Gran (2001) found that b values ranged from 0.3 to 0.5 for bedrock channels in six mountain drainage basins in Oregon, Washington, and California. They also found that bedrock channel width reflected the local influence of longitudinal patterns of bedrock erosivity, and in particular that bedrock channel width decreased substantially downstream at the contact between relatively weak limestone and more erosion-resistant granite. Snyder and others (2001) reported values of $b = 0.46$ and 0.65 for the high flow channel width of two channels in the King Range of the Northern California Coast. Snyder and others (2003) subsequently reported that $b = 0.21$ to 0.56, with most values between 0.3 and 0.5, for a larger sampling of channels in this area. Tomkin and others (2003) reported $b = 0.42$ for the Clearwater River, Washington, which flows across an order-of-magnitude decrease in rock uplift rates from the basin headwaters to the river's mouth. Van der Beek and Bishop (2003) reported that $b = 0.55$ and 0.53 for two rivers in southeastern Australia. Reviewing such previous studies, Whipple (2004) concluded that in general $b \approx 0.4$ was typical for many bedrock rivers.

As discussed by Tomkin and others (2003), there are many ways to parameterize models of bedrock incision, and few studies provide constraints on the most appropriate form. Whipple and others (2000a) discussed models of bedrock river incision by individual mechanical processes, and recognized that several processes may act in concert to set long-term bedrock lowering rates. Montgomery (2003) argued that the combined influence of processes actively incising into particular rivers could be represented by a ternary diagram with end-members defined by processes of abrasion, plucking, and weathering. Nonetheless, the unit stream power model remains attractive for modeling and exploring the long-term bedrock erosion potential of rivers in part because it explicitly incorporates the role of downstream changes in channel width.

Unit stream power is the product of the unit weight of water (γ), the discharge per unit channel width (Q/w) and channel slope (S). Hence, the bedrock incision rate (E), if assumed to be driven by unit stream power, may be expressed as

$$E \propto \gamma(Q/w)S \tag{1}$$

Substitution of power law relations between discharge and drainage area and between channel width and drainage area into equation 1 yields

$$E = KA^{\lambda}S \tag{2}$$

where K incorporates the effects of bedrock erodibility and the other constants, including the proportionality implied by equation 1, and λ incorporates the exponents in the power law relations employed to yield equation 2. Formulating a bedrock erosion law along the lines of equation 2 does not account for the potential for bedrock channel width to adjust to spatial gradients in lithology, channel slope, or rock uplift.

Field surveys from the Yarlung Tsangpo and Po-Tsangpo Rivers in eastern Tibet support the hypothesis that bedrock channel width responds to spatial gradients in rock uplift. In particular, field measurements of channel width from a wide range of basin sizes along a downstream transect across increasing long-term rock uplift rates indicate a systematic departure from classical width versus drainage area relations. These rivers flow through the eastern syntaxis of the Himalaya where young, deeply exhumed metamorphic rocks in the downstream portions of the basin contrast with relatively flat-lying Mesozoic sedimentary rocks in basin headwaters. River widths were measured using a tape measure or laser range finder at locations on a transect along the Po-Tsangpo River and its tributaries beginning in an upstream area with low erosion rates underlain by Tethyan sedimentary rocks and extending to where the river drops through a steep gorge to join the Tsangpo River in an area of rapid erosion and young metamorphic rocks (Burg and others, 1997; Zeitler and others, 2001). Field-measured channel widths correspond to the high-flow widths of Snyder and others (2001), as defined by evidence for recent scour and lack of vegetation.

During planning for field reconnaissance of the region it was anticipated that rates of river incision could be determined from dating of strath terraces. Although many local alluvial terraces were observed during a month-long field reconnaissance of the area, only several isolated water-polished bedrock surfaces were located despite vigilant surveillance of the terrain. The abundance of fill terraces likely reflects frequent landsliding in the area. Periods of episodic high sediment supply and transient changes in local base level due to landslide dams appear to characterize sediment transfer out of these mountains. Nonetheless, the relatively strong, erosion resistant bedrock forming the valley walls appears to inhibit strath formation by limiting lateral bedrock erosion rates.

Downstream along this transect, the width of small channels follows conventional width-drainage area scaling with $b \approx 0.4$ to 0.5. But the downstream rate of channel widening as a function of drainage area declines systematically as the river steepens through more deeply exhumed, and more rapidly eroding reaches (fig. 7). Whether this occurs because of a change in b or in c, bedrock channel width systematically responds as drainage area increases and the river flows into the rapidly eroding eastern syntaxis of the Himalaya. Montgomery and Gran (2001) showed that bedrock channel width narrowed across lithologic transitions from weaker to harder rocks in the Sierra Nevada. Hence, the systematic decrease in the apparent b values at Namche Barwa may simply reflect spatial gradients in erodibility as the river flows from Tethyan sedimentary rocks into the deeply exhumed metamorphic rocks of the syntaxis (and therefore the decrease may actually be due to spatially variable c values). Finally, downstream of the transect with field measurements, channel widths measured from satellite imagery (Finnegan and others, *submitted*) show that channel width systematically decreases downstream for some distance through the gorge of the Tsangpo River at Namche Barwa, an area of rapid erosion (Burg and others, 1997; Zeitler and others, 2001) predicted to have among the highest bedrock incision rates in the Himalaya (Finlayson and others, 2002). Regardless of whether the channel width is a primary or secondary adjustment, bedrock channel width at Namche Barwa responds to spatial gradients in rock uplift rates. This finding is consistent with those of Harbor (1998) who found

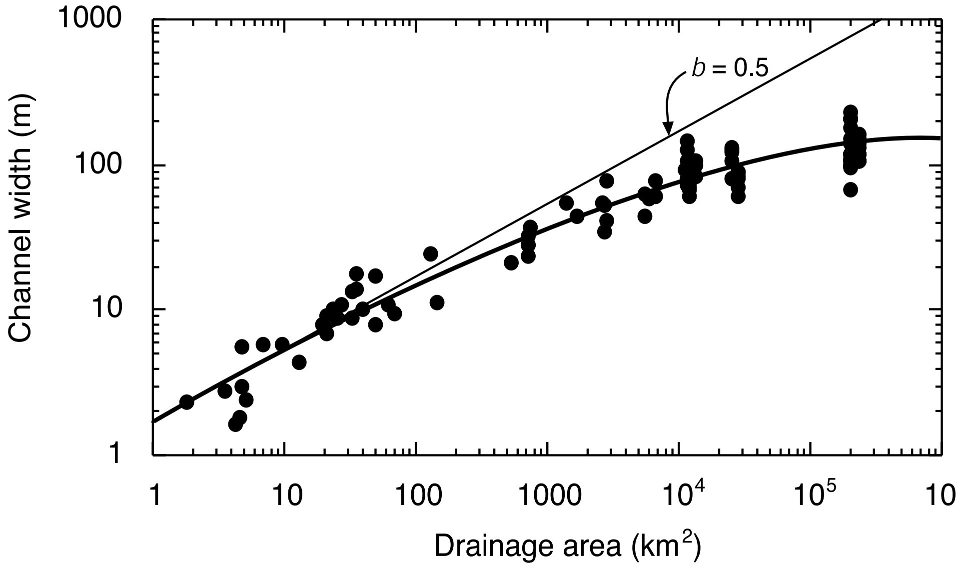

Fig. 7. Field measured channel width versus drainage area from channels along a transect down the Po-Tsangpo River in eastern Tibet; data for channels with drainage areas $>10^5$ km^2 are from the Tsangpo River through its gorge at Namche Barwa and were derived from satellite imagery.

evidence for channel narrowing and armoring where the Sevier River flowed across a zone of active rock uplift, and of Lavé and Avouac (2001) who found downstream decreases in valley width measured from satellite images through areas of rapid uplift in the central Himalayas.

Another potential explanation for the observed non-log-linear trend in width data for the area around Namche Barwa is that rainfall is not uniform across this area, and therefore that discharge does not scale linearly with drainage area. However, more rain falls per unit area in the area around the Tsangpo Gorge than in upstream areas we surveyed. Hence, the spatial variability in rainfall should tend to force the relationship between channel width and drainage area the other way than observed, as increasing precipitation downstream would favor larger-than-extrapolated widths to convey flow through the syntaxis. It is possible, however, that peak flows may not scale linearly with drainage area and that such an effect could potentially explain the drop off in the observed width versus drainage area scaling.

Nonetheless, extrapolating the relation between channel width and drainage area for $b = 0.4$ to 0.5 for the data from the small basins to larger basin sizes allows estimating the degree to which the channel narrows relative to the conventional expectation. Channels in the gorge of the Tsangpo River are about 100 to 200 meters wide, whereas the conventional expectation extrapolated from the size of smaller channels using $b = 0.4$ to 0.5 would predict a channel more like 400 to 700 meters wide. Although it remains unclear as to how to translate channel narrowing into erosional efficiency, this observed downstream change in channel width would, using the stream power law as expressed in equation 1, translate into a factor of 2 to 7 times the erosion rate in the gorge than for the small basins. Given that the background rate of erosion in the Himalaya is about 2 mm yr^{-1} (Galy and France-Lenord, 2001; Lavé and Avouac, 2001), this logic yields estimated incision rates of about 4 to 14 mm yr^{-1} for the Tsangpo River through its gorge at Namche Barwa.

The adjustment of bedrock channel width to spatial gradients in rates of rock uplift would lead to the potential for a feedback in which faster rock uplift leads to channel constriction, in turn, leading to faster erosion that inhibits valley widening. In addition to the widely acknowledged ability of channel slope to adjust to spatial gradients in rock uplift or bedrock erodibility, narrowing of bedrock channel width also appears to characterize the response of bedrock rivers to environmental forcing (Finnegan and others, *submitted*).

DISCUSSION

The observations discussed above come from rather different river systems and imply some simple underlying controls on patterns of strath terrace formation, that, if generalizable, have fundamental implications for understanding landscape evolution in mountain drainage basins. In my field experience, strath terraces with beveled bedrock surfaces are well developed and widespread in areas with poorly-indurated sandstone and siltstone, and are relatively rare in hard, resistant lithologies (table 1). Instead, I have found that water worked bedrock surfaces in hard rocks generally appear to be relatively small, isolated, and discontinuous features, observations consistent with those reported by others working in Himalayan rivers (for example, Burbank and others, 1996; Lavé and Avouac, 2001; Pratt and others, 2002). The generality of this pattern is bolstered by a synthesis of places where well-developed straths with extensive beveled bedrock surfaces have been reported and places where they have been described as weakly formed, ill-defined, or isolated exposures of water-worked bedrock.

In addition to the apparent lithologic control on the pattern of strath terraces in the Satsop and Teanaway rivers, I have observed extensive well-developed strath terraces in the Clearwater River, Washington [studied in detail by Pazzaglia and Brandon (2001) and Wegmann and Pazzaglia (2002)], the Nenana River near Denali in Alaska, and in the Rio Beni immediately upstream of where it flows out from the Andes in eastern Bolivia. All of these areas are underlain by Tertiary sandstone and siltstone. In contrast, I have observed little evidence of strath terrace formation in areas underlain by hard crystalline rocks, such as basalt-underlain portions of the Satsop River, as well as in the high-grade metamorphic rocks of the eastern Himalayan syntaxis along the Tsangpo River and its tributaries, and in rivers flowing over granite in the northern Cascade Range and Sierra Nevada. Strath terraces are also poorly developed where the Yakima River cuts through slowly rising Columbia River Basalt in the Yakima Folds in eastern Washington. In each of these areas, isolated exposures of water polished bedrock could be used to gauge rates of river incision, but in my experience rivers cut through hard, resistant bedrock lack extensive, well-defined strath terraces with beveled bedrock surfaces.

The locations where other workers have reported extensive strath terraces parallel these observations. Most reported sets of well-developed strath terraces occur in weak or partially indurated sedimentary rocks, whereas straths are not as well developed in hard rocks. J. Hoover Mackin (1937) described an extensive set of strath terraces cut into Cretaceous and Tertiary sandstones where the Wind River leaves older crystalline rocks in the Big Horn Basin of Wyoming. Hancock and others (1999) noted how downstream the Wind River strath terraces, carved into siltstones and mudstones, disappear where the river enters a narrow gorge through erosion-resistant Precambrian and Paleozoic rocks. Ritter (1967) described a series of well preserved strath terraces where rivers leave the hard Precambrian crystalline core of the Beartooth Mountains of southern Montana to flow over Cretaceous and Tertiary sedimentary rocks on the flank of the range. Personius and others (1993) described extensive well-developed strath terraces along coastal Oregon rivers cut into Tertiary marine

TABLE 1

Areas where strath terraces are extensive, with well-developed beveled bedrock surfaces, or are weakly developed or absent

Location	Lithology	Source
WELL DEVELOPED STRATHS		
Satsop River, Washington	Tertiary sandstone/siltstone	Personal observations
Teanaway River, Washington	Tertiary sandstone/siltstone	Personal observations
Nenana River, Alaska,	Sandstone	Personal observations
Rio Beni, Bolivia	Sandstone	Personal observations
Cache Creek, California	Sandstone/siltstone	G. Pasternack (personal communication)
Clearwater River, Washington	Sandstone/siltstone	Wegmann and Pazzaglia (2002)
Oregon Coast Range	Tertiary sandstone	Personius and others (1993); Personius (1995)
Wind River, Wyoming	Cretaceous/Tertiary sandstone	Mackin (1937); Hancock and others (1999)
Beartooth Mountains, Montana	Cretaceous/Tertiary sedimentary	Ritter (1967)
Fremont River, Utah	Sandstone and shale	Repka and others (1997)
Ventura River, Southern California	Miocene to Quaternary sediments	Rockwell and others (1984)
Bear, Mattole, and Ten Mile Rivers, Northern California	Mesozoic sandstone and siltstone	Merritts and others (1994)
Eel River, Northern California	Mesozoic to Cenozoic sandstone and shale	Seidl and Dietrich (1992)
Susquehanna River, Pennsylvania	Paleozoic and Mesozoic sedimentary	Pazzaglia and Gardner (1993)
Tien Shan, Western China	Mesozoic and Cenozoic sedimentary	Molnar and others (1994)
Siwalik Hills, Sub-Himalaya	Miocene to Pliocene sedimentary	Lavé and Avouac (2000)
Shagau River, Northern Tibet	Miocene red clay	Pan and others (2003)
Yellow River, Northern China	Mesozoic muddy sandstone	Cheng and others (2002)
Xidatan, Eastern Tibet	Mesozoic turbidites and phyllites	Van der Woerd and others (1998)
Huangarua River, New Zealand	Mesozoic graywacke and argillite	Formento-Trigilio and others (2003)
WEAKLY DEVELOPED STRATHS		
Satsop River, Washington	Basalt	Personal observations
Yakima River, Washington	Basalt	Personal observations
Northern Cascades, Washington	Granite	Personal observations
Sierra Nevada, California	Granite	Personal observations
Tsangpo River, Eastern Tibet	High grade metamorphics	Personal observations
Teanaway River, Washington	Basalt	B. Collins (personal communication)
Susquehanna River, Pennsylvania	High grade metamorphics	Pazzaglia and Gardner (1993)
Alaknanda River, Northern India	Medium grade schist, gneiss, quartzite	Barnard and others (2001)
Indus River, Northern Pakistan	High-grade metamorphic and igneous	Burbank and others (1996); Leland and others (1998)
Trans-Himalayan Rivers, Eastern Nepal	Medium- to high-grade metamorphics	Lavé and Avouac (2001)

sedimentary rocks. Personius (1995) also noted how longitudinally continuous, wide straths were preferentially developed in weak sedimentary lithologies and that Oregon Coast Range rivers flowing on hard, dense bedrock were "restricted to narrow gorges." Pazzaglia and Gardner (1993) described a similar pattern of strath terrace development on the lower Susquehanna River, Pennsylvania. They reported that straths with well defined terrace treads occur where the river flows over Paleozoic and Mesozoic sedimentary rocks but that the river becomes restricted to a narrow, steep-walled gorge where it flows over hard, erosion-resistant rocks (amphibolite-grade gneiss, schist, phyllite and quartzite). Similarly, Lavé and Avouac (2001) reported that along trans-Himalayan rivers in eastern Nepal the well-developed fluvial terraces carved into the sedimentary rocks of the sub-Himalaya give way to steep gorges lacking strath terraces in the harder rocks of the Greater Himalaya.

Many other studies report well-defined strath terraces cut into sedimentary rocks. Rockwell and others (1984) used deformed strath terraces cut into Miocene to Quaternary sedimentary units along the Ventura River to estimate fault offset rates in southern California. Molnar and others (1994) described deformed strath terraces cut in Mesozoic and Cenozoic sedimentary rocks on the northern flank of the Tien Shan in western China. Strath terraces of Jinshaan Canyon, on the Yellow River in Northern China are cut into Mesozoic muddy sandstones, conglomerate and pyroclastic rocks (Cheng and others, 2002). Similarly, Lavé and Avouac (2000) analyzed deformation of well-developed strath terraces cut into upper Miocene to Pleistocene sedimentary rocks of the Siwalik Hills in the sub-Himalaya. Merritts and others (1994) documented extensive strath terraces along the Bear, Mattole, and Ten Mile rivers, in areas underlain by Mesozoic sandstones and mudstones on the northern California Coast. Seidl and Dietrich (1992) investigated the relation between knickpoint migration and pronounced strath terraces on the northern California Coast along the Eel River and Elder Creek where the channels flow over Mesozoic and Cenozoic graywacke and shale. The extensive strath terraces of the Clearwater River on the Olympic Peninsula, Washington, also are cut into Cenozoic marine sandstone and siltstone (Pazzaglia and Brandon, 2001; Wegmann and Pazzaglia, 2002). Repka and others (1997) dated strath terraces cut into sandstone and shale bedrock along the Fremont River, Utah. Formento-Trigilio and others (2003) analyzed the deformation of strath terraces cut into Upper Miocene marine sediments and Mesozoic graywacke and argillites on the Huangarua River in New Zealand. In summary, reports of extensive, well-developed strath terraces with characteristic beveled bedrock surfaces come from areas underlain by relatively weak sedimentary rocks—typically argillaceous sandstone, siltstone, and mudstone.

In contrast, workers studying river incision in regions of hard rocks generally report that erosional terraces are spatially restricted, discontinuous, and topographically irregular, with substantial relief preserved on the water worn surfaces. Although the features described in published field observations are clearly fossil streambeds, these features bear little resemblance to the broad beveled bedrock surfaces originally referred to as strath terraces. Burbank and others (1996) and Leland and others (1998) reported numerous small, water-worked surfaces along the Indus River where it incises through deeply exhumed crystalline rocks in the western syntaxis of the Himalaya. They noted that these eroded surfaces had relief of 1 to 10 meters and consisted of small surfaces 10 to 200 meters wide that lacked downstream continuity. Photographs and descriptions in Barnard and others (2001) depict similar small, discontinuous water-worked surfaces preserved along the Alaknanda River where it flows through medium grade metamorphic rocks in the Garhwal Himalaya of northern India. Pratt and others (2002) reported small, discontinuous fluvially-sculpted bedrock surfaces along the Marsyandi River where it flows over medium to high-grade gneiss in the Greater Himalaya of central Nepal. Pazzaglia and Gardner's (1993) observations on the Susquehanna River also indicate local preservation of water-worked surfaces but limited strath terrace development where the river flows over crystalline rocks. It appears that in general strath terraces in hard, erosion-resistant rocks tend to be ill-defined, discontinuous, spatially limited areas of water-polished channel bed abandoned and preserved locally as the river incised.

These observations lead me to conclude that there is a strong lithologic control on the development of strath terraces with well-defined beveled bedrock surfaces.

Channel Width, Floodplain Width, and Strath Terrace Formation

In his classic study of the *Geology of the Henry Mountains*, G. K. Gilbert (1877) noted that the ability of a river to carve into bedrock depended on the exposure of the bed and that the ability of a river to carve a floodplain depended on the relationship between the ability of the river to incise and to erode bedrock banks.

> ". . . downward wear ceases when the load equals the capacity for transportation. Whenever the load reduces the downward corrasion to little or nothing, lateral corrasion becomes relatively and actually of importance. The first result of the wearing of the walls of a stream's channel is the formation of a floodplain" (Gilbert, 1877, p. 126-127).

Gilbert also noted that lithology influenced the ability of channels to carve wide floodplains into bedrock because of the influence of lithology on channel slope, and therefore sediment transport and bed cover. In the Henry Mountains, rivers flowing over strong rocks had narrow floodplains, whereas those flowing over weak rocks formed wide, open valleys underlain by a beveled bedrock surface. As envisioned by Gilbert, a lithologic control on channel slope could explain the spatial distribution of wide bedrock-cored valley bottoms, and therefore strath terraces, because reaches flowing over weak rocks have lower slopes than reaches flowing over harder rocks. This lithologic control leads to greater sediment storage and extensive bed cover that protects the bed from erosion in areas underlain by weak rocks and thereby promotes lateral erosion and valley-bottom widening.

The ability to preferentially erode bedrock channel banks would provide an additional mechanism to favor development of wide valley bottoms, and thereby create potential strath terrace surfaces in rocks susceptible to rapid lateral bank erosion. In particular, the slaking that characterizes lowering of some sub-aerially exposed sedimentary rocks provides a simple mechanism for rapid valley widening in rocks susceptible to the process because the exposed bedrock channel banks erode at rates orders of magnitude faster than the wet (and therefore strong) channel bed. Hence, weak rocks that fall apart upon sub-aerial exposure promote strath formation as a natural consequence of the difference in the erodibility of sub-aerially exposed bedrock channel bed, banks, and valley walls and that of the intact, hard rock exposed in the perennially inundated thalweg. Whereas one would expect to see extensive, well-developed strath terraces in lithologies susceptible to slaking due to wetting and drying (or in response to other accelerated surface weathering phenomena, such as freeze-thaw shattering), rivers flowing over rocks that remain hard upon sub-aerial exposure tend to become confined within narrow valleys and to form gorges in response to locally high rock uplift rates.

The role of an asymmetry in bedrock erodiblity in favoring strath terrace formation where the slaking mechanism is active is not to say that strath terraces cannot form in hard rocks, even if such occurrences are relatively uncommon. Although a strong asymmetry in erodibility means that the bed need not be protected by alluvium to create a beveled bedrock surface, the two processes would act to reinforce one another. Protection of the channel bed by alluvium would initiate a feedback wherein the rate of bedrock incision would be minimized because the bedrock exposed in the bed would be both wet (and therefore strong) and covered by a protective blanket of alluvium. Together the respective effects of periodicity in the sediment supply, and therefore the extent of bed cover, and an asymmetry in bed and bank erodibility can explain the temporal and spatial distribution of strath terraces. Pulses of bed-protecting alluvium may set the timing of strath formation in many landscapes, whereas the spatial distribution of well-developed strath terraces may be controlled primarily by lithology.

If sub-aerially exposed rock in the valley walls is as strong as that exposed on the channel bed, then the channel cannot widen fast enough to form a wide strath terrace and instead channel incision will result in a narrow bedrock valley or a gorge. Bedrock erosion rates for conventional processes in which bed lowering is a function of flow depth (such as by shear stress or unit stream power) predict maximum erosion rates in the deepest flow. In this case, mechanical erosion of the bedrock valley walls should proceed at a slower rate than lowering of the channel bed — a condition that would tend to inhibit development of strath terraces in erosion resistant lithologies. Hence, in hard rocks where shear stress or stream power (whether through plucking, abrasion, or other mechanisms related to the energy of the flow) is the primary driving mechanism for bedrock incision, the bedrock channel bed erodes faster than bedrock channel banks, unless as shown by Sklar and Dietrich (1998) and exploited by Hancock and Anderson (2002), abundant bedload protects the thalweg and thereby promotes erosion of channel banks. However, if the valley walls are weak (and friable) then reducing the rate of river incision by a reduced channel slope that retains bed cover could allow for valley widening at a rate of cms yr^{-1}.

The necessary condition for the formation of wide, well-developed strath terraces is a period of sustained lateral bedrock erosion of the valley walls at a rate well above the rate of bedrock channel incision, followed by a period of rapid incision and floodplain abandonment. Rates of river incision into bedrock are typically less than 1 mm yr^{-1}, but can reach 2-5 mm yr^{-1} in rapidly uplifting mountain ranges such as the central Himalaya and Taiwan, and locally reach 10 mm yr^{-1} in the most rapidly eroding terrain (Whipple and others, 2000b; Burbank, 2002). In most circumstances valley wall or bedrock channel-bank erosion controlled by the slaking length scale of mm to cm would set up conditions conducive to strath development under most reasonable rates of bedrock channel incision.

The potential for very rapid lowering of bedrock channel beds when susceptible lithologies are exposed would lead to a feedback that would favor river long profiles adjusted to track the condition for creation of an alluvial bed cover. Exposed bedrock beds would tend to erode faster until the slope was reduced enough to support bed cover. Conversely, thick bed cover would retard bed erosion enough to result in progressive steepening of the channel in areas of active rock uplift. Montgomery and others (1996) showed that the transition from alluvial to bedrock channel beds in the West Fork Satsop River followed an inverse drainage area-slope dependence. Massong and Montgomery (2000) and Montgomery and others (2003) subsequently reported that similar relationships characterized the transition from alluvial to bedrock channel beds in the coastal ranges of Oregon and Washington. Rapid erosion of exposed bedrock beds, combined with far slower erosion of the bedrock below alluvial bed cover would, over time, tend to make river long profiles approach the condition for converting a bedrock bed into an alluvial bed and would therefore favor the development of mixed alluvial/bedrock morphologies typical of many mountain drainage networks. Hence, if the rate of incision slows down dramatically once the channel bed is covered by alluvium, then river slopes, and therefore longitudinal profiles, may be governed in such circumstances by the criteria for sustaining a stable bed cover rather than the magnitude of the local sediment flux (Stock and others, 2005).

Conclusions

As recognized by Gilbert (1877), and recently reiterated by Hancock and Anderson (2002), the conditions necessary to form extensive strath terraces reduce to the ratio of the lateral to vertical bedrock incision rate and strath formation therefore requires a period of relative thalweg stability. In alpine landscapes with high erosion rates, and therefore high river incision rates, it would require implausibly high lateral valley wall erosion rates to create wide strath terraces in all but the weakest rocks. Put simply, it is difficult for valley widening to outstrip channel incision where incision is fast. In addition, it would be difficult to form strath terraces in exposed deeply exhumed, mechanically strong rocks capable of resisting lateral widening. Although additional factors such as fracture density and material discontinuities also greatly affect rock strength (Selby, 1982; Schmidt and Montgomery, 1995), field observations and measurements of bedrock erosion processes in relatively weak sedimentary rocks indicate that valleys could widen much faster than long-term bedrock incision rates in areas where rocks become substantially weaker when raised above the water table, thereby promoting development of beveled bedrock surfaces.

Altogether the observations discussed above suggest a strong lithological control on the development, and therefore the geography, of extensive strath terraces. While there certainly are other complementary influences and controls on strath terrace formation, the observations discussed above help to frame conceptual models about how to interpret fluvial portions of landscapes. In particular, they imply that extensive, well-developed strath terrace sequences tend to form in relatively weak rocks, whereas narrow canyons and gorges with irregular, isolated remnants of water-worked surfaces tend to characterize rivers flowing over hard, erosion resistant rocks.

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