

Rates and mechanisms of bedrock incision and strath terrace formation in a forested catchment, Cascade Range, Washington

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ABSTRACT

Measurements of channel bed and bank incision into bedrock coupled with mapping and radiocarbon dating of strath terraces in the West Fork Teanaway River, Washington, provide insight into rates and mechanisms of river incision and strath terrace formation in a forested landscape. The West Fork drains 102 km² of the slowly exhuming southeastern North Cascade Range, and it is rapidly eroding its bed and creating strath terraces in its lower reach. Minimum vertical incision, measured annually relative to nails embedded in the streambed, was greater in the seasonally exposed, weathering-dominated, high-flow channel (mean = 10.9 mm yr⁻¹) than in the perennially wet, abrasion-dominated, low-flow channel (3.8 mm yr⁻¹), documenting unsteady lowering of the channel margin. Ages of radiocarbon-dated materials from alluvium on strath terraces, 0.1 m to 5.4 m above the water surface, suggest three episodes of strath abandonment at maximum ages of ca. A.D. 830, A.D. 1560, and A.D. 1890, and average incision rates of 1.3 mm yr⁻¹, 1.4 mm yr⁻¹, and 7.4 mm yr⁻¹ for the oldest to youngest surfaces, respectively. Weathering-promoted vertical incision in the high-flow channel provides a mechanism for “top-down” rapid lateral strath planation in which scour of alluvium on incipient strath terraces incorporates the surface into the high-flow channel, allowing rapid removal of bedrock weathered during wetting and drying cycles. Relationships among channel width, channel confinement by bedrock terrace risers, modeled bankfull shear stress, and alluvial bed cover suggest that rapid channel widening could also internally limit vertical incision by slowing incision as shear stresses decline and more alluvium is retained on the bed. The timing of the most recent (ca. A.D. 1890)

strath abandonment corresponds with historical anthropogenic removal of fluvial wood, suggesting that the relative abundance of fluvial wood may influence episodes of vertical bedrock incision by affecting the retention of alluvium on streambeds.

INTRODUCTION

Bedrock incision by rivers drives the topographic evolution of mountain landscapes and can leave a morphologic signature in the form of strath terraces, which provide important records for interpreting tectonic and climatic history (Pazzaglia, 2013). Because of bedrock incision's importance, it has been the subject of a number of theoretical and experimental (see review by Lamb et al., 2015) and field studies (e.g., Hancock et al., 1998; Tinkler and Parish, 1998; Whipple et al., 2000; Hartshorn et al., 2002; Stock et al., 2005; Johnson et al., 2010; Lamb and Fonstad, 2010; Cook et al., 2013; Inoue et al., 2014). However, few studies have linked incisional processes with lateral planation of straths or their subsequent incision and stranding as strath terraces (e.g., Montgomery, 2004; Finnegan and Balco, 2013; Johnson and Finnegan, 2015). Here, in a field study of a river that is rapidly eroding its bed and creating strath terraces, we measured annual vertical and lateral incision to address theoretical and laboratory predictions on the relative roles of erosion and weathering processes in shaping channels (e.g., Hancock et al., 2011; Small et al., 2015). We then coupled these measurements with incision rates determined from strath terraces using radiocarbon dating, and we propose a mechanism of rapid strath planation and how it may, by adjusting channel morphology, internally limit incision.

Background

Bedrock channels erode by processes that include abrasion (removal of rock by impact from saltating particles in the bed load or in sus-

pension), macro-abrasion (fracturing of the bedrock into pluckable or entrainable sizes through the collision with particles in transport), plucking (hydraulic removal of blocks), dissolution, and cavitation (Whipple et al., 2000). The dominance and efficacy of an erosional process in a natural channel depend in part on lithology, joint spacing, fractures, and bedding planes (Whipple et al., 2000). Physical and chemical weathering can greatly enhance erosional processes (Howard, 1998; Whipple et al., 2000; Stock et al., 2005; Hancock et al., 2011; Han et al., 2014; Small et al., 2015) by increasing roughness (Hancock et al., 1998; Huda and Small, 2014) and decreasing rock strength and thereby enhancing susceptibility to abrasion, expanding fractures along which blocks are removed by plucking (Hancock et al., 1998; Whipple et al., 2000), and comminuting rock into smaller fragments (Stock et al., 2005).

The efficacy of at least some erosional and weathering processes is also influenced by the thickness of alluvial cover. For example, laboratory experiments predict maximum abrasion of streambeds having partial bedrock exposure associated with intermediate sediment supplies that provide the “tools” for abrading the bed without protecting the bed from abrasion (Sklar and Dietrich, 2001). While most applications of this concept to interpreting river incision histories have focused on regional- or basin-scale influences on stream power or the supply and caliber of sediment (e.g., changes to base level, climate, or tectonic uplift rates), reach-scale processes that control the routing or retention of sediment in channels, such as landslides that form temporary dams in rivers, could control rates of bedrock incision by altering the distribution of alluvial and bedrock reaches (e.g., Ouimet et al., 2007). In forested regions, such a mechanism could also be provided by in-channel wood accumulations, which can transform channels from bedrock to alluvial by altering the balance between sediment transport and supply (Montgomery et al., 1996).

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Cross-channel variation in processes and rates of bedrock incision shapes channel cross-sectional and planform geometry, which in turn controls hydraulics and the distribution of erosive power across the channel (for review, see Hancock *et al.*, 2011). Differential incision rates in a channel's low-flow and high-flow bed (in this paper, we use "low-flow channel" interchangeably with "channel thalweg" and "high-flow channel" interchangeably with "channel margins") can result from differences in weathering (Stock *et al.*, 2005; Hancock *et al.*, 2011; Small *et al.*, 2015) or from whether cover or tool effects dominate (Turowski *et al.*, 2008). Differences in rock erodibility can also be a primary influence on the shape of river longitudinal profiles (Duvall *et al.*, 2004; Allen *et al.*, 2013). Locally rapid incision is often associated with knickpoints that propagate upstream or that initiate in steeper, smaller-drainage-area parts of a channel network (Crosby and Whipple, 2006). However, several field studies suggest that adjustments to channel width may be as important as changes to channel gradient in maintaining locally high incision rates across longitudinal variations in rock resistance (Montgomery and Gran, 2001) or uplift rates (Duvall *et al.*, 2004; Amos and Burbank, 2007; Whitaker *et al.*, 2007; Turowski *et al.*, 2009; Yanites *et al.*, 2010).

The control alluvial cover exerts on vertical incision implies that lateral erosion dominates in periods when sediment supply is relatively high, and terrace-forming incision dominates when sediment supply is relatively low and the alluvial bed cover thins (Bull, 1990; Pazzaglia and Brandon, 2001). Hence, temporal variation in either sediment or water supply could alter the ratio of vertical to lateral erosion and either create straths (a valley-bottom surface created by lateral stream cutting; Bucher, 1932) or incise and abandon them, creating strath terraces (abandoned, alluvium-mantled straths, the surface of which is referred to as the tread); this conceptual model is commonly used to interpret the genesis of straths and strath terraces (e.g., Personius *et al.*, 1993; Wegmann and Pazzaglia, 2002; Fuller *et al.*, 2009). By extension, the effects of landslide dams (Ouimet *et al.*, 2007), wood accumulations (Montgomery *et al.*, 2003), or other controls on the retentivity of alluvium could also influence whether rivers erode vertically or laterally into rock.

Relative to vertical bedrock incision, less is known about processes and controls on lateral bedrock erosion, but lithology has been demonstrated to influence the dominant process of lateral bedrock erosion (Wohl and Ikeda, 1998; Lavé and Avouac, 2001; Montgomery and Gran, 2001; Wohl and Merritt, 2001; Wohl and Achy-

than, 2002; Finnegan *et al.*, 2007; Spotila *et al.*, 2015) or susceptibility to weathering (Hancock *et al.*, 2011; Johnson and Finnegan, 2015), and thus the efficacy of lateral strath planation of bedrock channels (Montgomery, 2004; García, 2006; Wohl, 2008). Channel planform may also influence rates and patterns of lateral erosion; Finnegan and Balco (2013) suggested that a braided channel is more likely to accomplish lateral planation because the channel is more prone to incise laterally along both margins, rather than just one margin.

Incision and terrace creation have long been recognized as inherently unsteady (Gilbert, 1877; Mackin, 1937; Bull, 1990) due to temporal variation in uplift (e.g., Pazzaglia and Gardner, 1993; Schoenbohm *et al.*, 2004), base-level fall, and knickpoints that propagate upstream (e.g., Harvey and Wells, 1987; García *et al.*, 2004; Bishop *et al.*, 2005), or climate-forced variations in the relative supply of water and sediment (e.g., Pazzaglia and Brandon, 2001; Hancock and Anderson, 2002; Wegmann and Pazzaglia, 2002; Gibbard and Lewin, 2009; Fuller *et al.*, 2009). More recently, it has been proposed that strath terraces can form in the absence of external tectonic or climate forcing, due to internal forcing as meander cutoffs force local knick zones (Finnegan and Dietrich, 2011) or by unsteady meandering arising from spatial contrasts in bank strength (Limaye and Lamb, 2014). In forested regions, where wood jams can remain stable for long periods—in the Pacific Northwest for over 1000 yr in some cases (Hyatt and Naiman, 2001; Montgomery and Abbe, 2006)—and can trigger avulsions, fluvial wood accumulations could also be a viable mechanism for internal forcing of strath incision.

Hancock and Anderson (2002) numerically simulated strath terrace formation in response to temporally changing water and sediment discharge associated with Quaternary climatic fluctuations and proposed that rivers that incise and create strath terraces spend a large amount of time in lateral planation and relatively little time vertically incising. This proposal was supported by a study that used a large number of radiocarbon dates from Holocene strath terraces (Wegmann and Pazzaglia, 2002) to determine that periods of vertical incision last only 25% of the cycle of strath creation and subsequent incision that creates a strath terrace. Incisional unsteadiness results in a dependence of average incision rates on the time interval over which the rate is measured, commonly referred to as the Sadler effect (Sadler, 1981), and averaged incision rates inferred from strath terraces have been observed to decline with increasing time interval (Gardner *et al.*, 1987; Mills, 2000; Finnegan

et al., 2014). However, Gallen *et al.* (2015) recently proposed this effect could, in many rivers, be the result of a systematic bias introduced by use of the modern streambed as the datum for measuring terrace heights.

Approach

To investigate how different erosional processes operate in space and time to vertically and horizontally incise rivers and create straths, we undertook a field study of a rapidly incising river in a region with slow rock uplift and no known active faulting, the forested West Fork Teanaway River in the southeastern North Cascades of Washington State (Fig. 1). Previously, we reported 1 yr average bedrock incision from the study site (Stock *et al.*, 2005). Here, we report direct field measurements of vertical bed incision and lateral bank recession measured relative to nails in the riverbed and banks annually over a 4 yr period and by repeat surveying of channel cross sections over a 7 yr period, document differential rates of incision in the high-flow and low-flow portions of the channel, and relate the differential to spatial variation in process and temporal variation in streamflow. We also map strath terraces along the 3-km-long reach of the river in which our erosion measurements were made, and we use radiocarbon dating to determine the ages of basal alluvium in strath terraces. We use these observations to explore the controls on bedrock incision and strath terrace formation over the last two millennia.

STUDY AREA

The West Fork Teanaway River originates in rugged, high-relief terrain near the crest of the Cascade Range (Fig. 1). Long-term exhumation rates in this region determined from apatite (U-Th)/He cooling are on the order of 0.05 mm yr⁻¹ (Reiners *et al.*, 2003), similar to the postglacial denudation rate of 0.08 mm yr⁻¹ determined from detrital ¹⁰Be concentrations in the Peshastin Creek basin adjoining the Teanaway River basin to the northeast (Moon *et al.*, 2011). The river is confined by a steep-sided valley in its upper watershed, where the bedrock is a moderately indurated sandstone of the Eocene Swauk Formation and harder basalt and andesite of the Teanaway Basalt (Tabor *et al.*, 1982). This steep, high-relief upper watershed transitions abruptly to lower-relief, rounded topography at the contact of the Eocene Roslyn Formation, a poorly indurated, medium- to fine-grained, micaceous, lithofeldspathic sandstone with beds of siltstone, conglomerate, and pebbly sandstone (Tabor *et al.*, 1982).

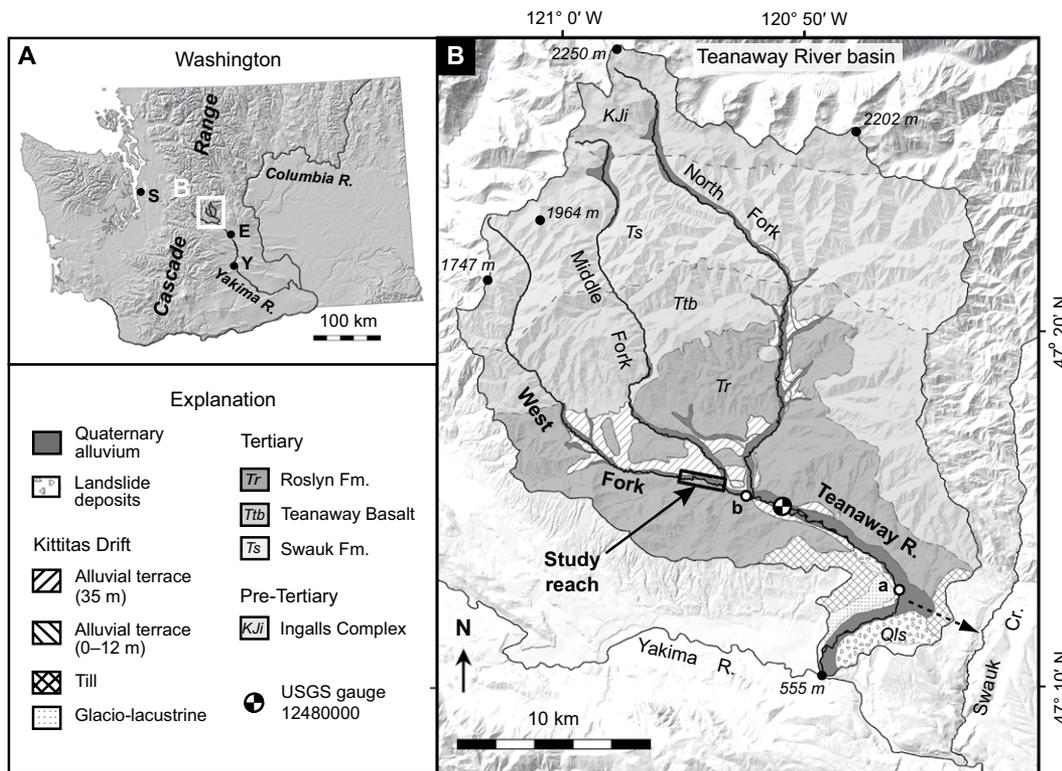


Figure 1. (A) Location of the Teanaway River drainage in the southeast North Cascade Range of Washington. S—Seattle; Y—Yakima; E—Ellensburg. (B) Generalized geology of the Teanaway River drainage, from Tabor et al. (1982). Dashed arrow shows possible Pleistocene path of Teanaway River (Saunders, 1914). Points along the main-stem Teanaway River labeled “a” and “b” are strath terraces sampled for radiocarbon dates (Table 5).

In this lower watershed underlain by the Roslyn Formation, the West Fork flows in a valley that is 0.2–0.5 km wide and floored by Holocene alluvium (Tabor et al., 1982) generally <3 m thick. In the upper 9 river kilometers of the 12 river kilometers of the lower watershed, the channel bed generally consists of a veneer of alluvium with interspersed patches of exposed bedrock, but the channel is not incised into bedrock (Fig. 2). However, in its lowermost 3 river kilometers, the channel is incised up to 6 m into the Roslyn Formation, and bedrock is commonly exposed in the riverbed. In this lowermost 3 river kilometers, the surface of the alluvial valley fill steps downward in flights of strath terraces formed in the Roslyn Formation (Fig. 3).

The lower West Fork Teanaway River valley was repeatedly overrun by Pleistocene ice that overtopped the ridge separating the Teanaway River from the drainage to the west (Porter, 1976). Terraces of basaltic outwash gravels of the Swauk Prairie subdrift of the Kittitas drift, possibly dating to the penultimate glaciation 130,000–140,000 yr ago, crop out ~35 m above the West Fork’s valley floor (Porter, 1976; Tabor et al., 1982). Saunders (1914) speculated that the Teanaway River once flowed east into the underfit Swauk Creek (Fig. 1) and that a prominent moraine of the Swauk Prairie subdrift (Tabor et al., 1982) may have forced the river’s diversion and capture to its present course.

The drainage basin of the West Fork (102 km² at its confluence with the Middle Fork and 92 km² at the incision measurement sites) receives, on average, 1006 mm of precipitation annually (USGS, 2012). The basin, between 684 m and 1964 m in elevation, is typically snow covered in winter. Runoff, measured at U.S. Geological Survey (USGS) gauge 12480000 on the Teanaway River (drainage area 445.5 km²; Fig. 1), peaks with snowmelt in May; over one half of annual runoff (56%) occurs in March, April, and May. Less than 3% of annual runoff occurs in the three low-flow months of August–October. Mean annual runoff estimated from a 44 yr period of record at USGS gauge 12480000 and extrapolated to the study reach is 5.65 m³ s⁻¹ in the 3 mo snowmelt period of March–May and 0.28 m³ s⁻¹ in the 3 mo low-flow period of August–October. Peak annual flows during spring runoff, extrapolated to our study site, are 11.9 m³ s⁻¹ for a 1.5 yr recurrence and 46.7 m³ s⁻¹ for a 50 yr recurrence (Fig. 4).

Forests in the West Fork Teanaway River valley are dominated by Douglas fir (*Pseudotsuga menziesii*) and ponderosa pine (*Pinus ponderosa*). Black cottonwood (*Populus trichocarpa*) and red alder (*Alnus rubra*) are also common along stream banks. Fire was historically frequent in the lower Teanaway River drainage, with large fires (>4000 ha) occurring every 27 yr over the 433 yr period between 1662 and 1995, and every 11 yr, on average, between 1708 and

1889, and coinciding with periods of annual and seasonal drought (Wright and Agee, 2004).

Streamside forests deliver abundant wood to Pacific Northwest rivers; the resulting fluvial wood and wood accumulations (wood jams) are fundamental to channel form and dynamics, including by trapping alluvium on what otherwise would be bedrock channel beds (e.g., Montgomery et al., 1996). A field survey of unmanaged streams in the Yakima Basin found 72.7 pieces of fluvial wood km⁻¹ and 13.8 wood jams km⁻¹ on average (McIntosh et al., 1994). Historical field observations and photographs (Fig. 5A) in the adjoining Middle Fork Teanaway River made by geologist Israel Russell (1898; Russell probably made his observations in 1892 [Russell, 1893]) indicate that in several places jams diverted the river from its former course and forced the river to excavate new channels. He reported that jams “usually started by the falling of a large tree across a stream,” which would then become plugged by wood, sand, and mud, and described a jam that completely diverted the channel by filling it “with drift-wood to a depth of twenty feet for a distance of some three hundred yards” (Russell, 1898, p. 243). Current wood loads in Pacific Northwest streams subject to historical management and land use are generally much lower than in the presettlement period (Sedell and Luchessa, 1981; Collins et al., 2002); currently wood is uncommon in the West Fork Teanaway River.

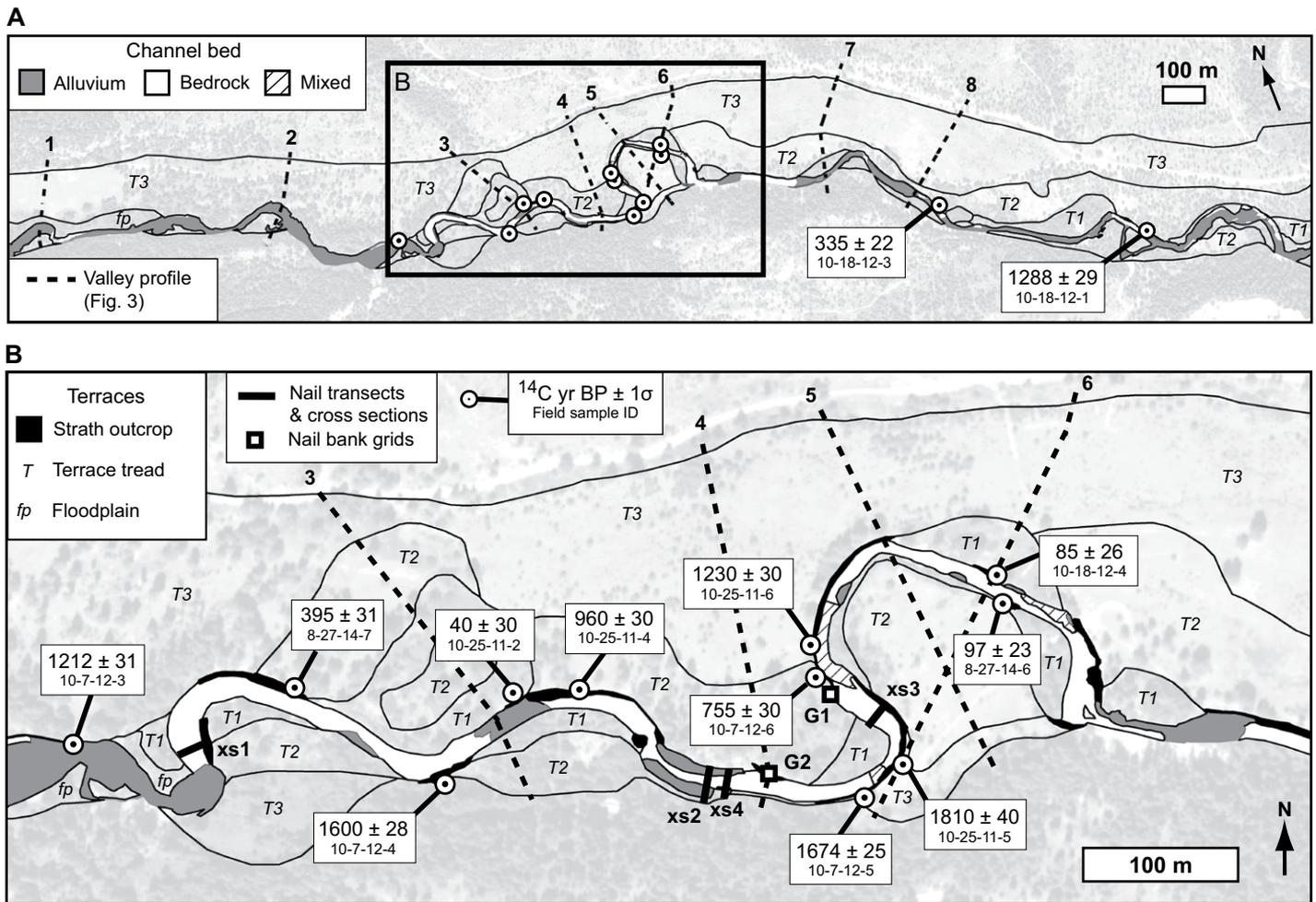


Figure 2. (A) Map of the lower West Fork Teanaway River valley showing field-mapped alluvial valley surfaces, occurrence of alluvium and bedrock channel bed segments, location of nail-incision transects, and location of radiocarbon-dated samples from basal alluvium on straths. (B) Detail of portion of study area in which nail measurement sites are located. Direction of river flow is from left to right.

Each one of the three forks of the Teanaway River was historically splash dammed. According to oral histories, beginning in 1891, temporary dams were built on each fork, filled with water during spring high flow, and then dynamited, with demolition timed so that the resulting flood waves from each fork would arrive at the main stem simultaneously (Kittitas County Centennial Committee, 1989). These log drives down the Teanaway River (Fig. 5B) lasted until 1911 or 1912 (Kittitas County Centennial Committee, 1989); subsequent to these two decades of splash damming, logs were transported by logging railroads, one of which was built along the north bank of the West Fork Teanaway. Splash dams and log drives such as those formerly widespread in the Pacific Northwest (Sedell and Luchessa, 1981) typically widened and scoured both alluvium and wood from streams (e.g., Schmall and Wesche, 1989; Tornlund and Ostlund, 2002).

Bedrock is exposed most commonly in a reach 1.5–3.0 km upstream from the Middle Fork confluence (Fig. 2A). The perennially wet, low-flow streambed in this reach is generally polished and sculpted by ~0.1–1.0-m-wide erosional flutes (Fig. 6A). Outside the low-flow channel but within the bankfull channel, the rock is generally friable, with folia commonly ~0.01–0.1 m thick, some of which expand upward and form “tents” during the dry season (Fig. 6B), and with blocks forming along bedding planes and joints. Within this 1.5 km reach, there are three prominent steps in the longitudinal profile (e.g., Fig. 6C). Steps are deeply fluted with plunge pools at their base, and step lips are actively backwearing, including by hydraulic removal of large bedrock blocks.

Bed sediment in the study area is primarily derived from the relatively hard basaltic and andesitic rocks from the river’s headwaters

or from various lithologies contained in glacial deposits; by contrast, alluvium from the Roslyn Formation breaks down rapidly, and tributaries in the lower watershed draining the Roslyn Formation produce almost entirely sand. The subsurface median grain size in the West Fork, determined from nine bulk samples, ranges from 13.1 mm to 18.6 mm (Watson, 1991); our measurements of the surface median grain size in 2002, using a Wolman surface-layer pebble count on gravel bars nearest to nail transects that we installed to measure bed incision (Fig. 2B), range from 61.5 mm to 80 mm.

Downstream from the West Fork’s confluence with the North and Middle Forks, the main-stem Teanaway River valley is ~0.5 km wide (Fig. 1). In several locations along the main-stem Teanaway River, narrow strath terrace remnants crop out along both valley margins, 3–4 m above the present-day riverbed.

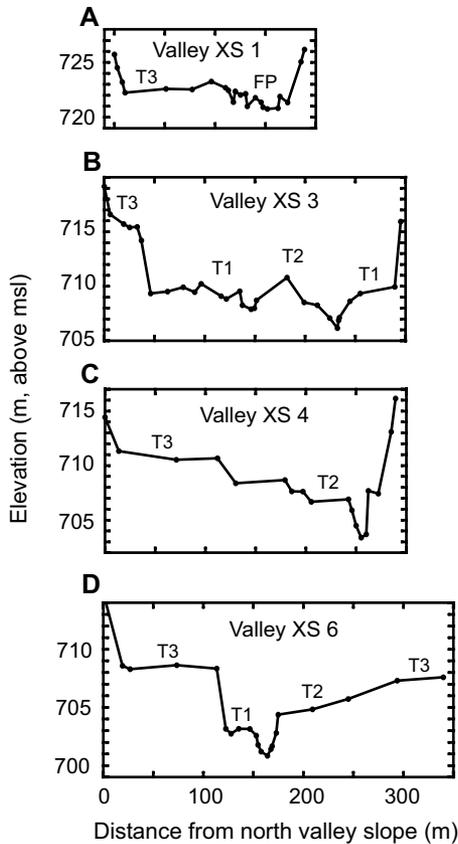


Figure 3. Representative field-surveyed valley-bottom topographic profiles at locations indicated in Figure 2. XS—cross section; FP—floodplain.

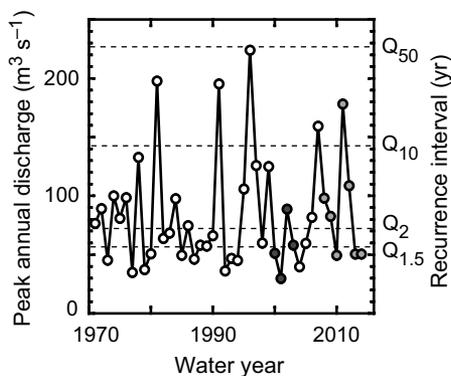


Figure 4. Peak annual daily flow at U.S. Geological Survey gauge 12480000, Teanaway River, below forks near Cle Elum, Washington, water year (WY) 1971 to WY 2013. Data are from U.S. Bureau of Reclamation. Flood recurrence intervals (dashed horizontal lines) are log Pearson probabilities calculated from the 43 yr period of record. Black circles indicate the 4 yr between nail measurements (1999–2003), and gray circles indicate the 7 yr between repeat cross-section surveys (2007–2014).

METHODS

To characterize rates and mechanisms of bedrock incision, we measured bed and bank erosion relative to nails installed flush into holes drilled in the riverbed and banks, at the time of installation and then annually between 1999 and 2003, and by repeated survey of stream cross sections between 2007 and 2014. To characterize reach-scale channel characteristics associated with active bedrock incision, we described patterns of channel slope and bankfull shear stress using field-surveyed channel dimensions and slopes relative to the field-mapped occurrence of alluvium and bedrock. To describe strath terraces and make inferences on the factors controlling their development, we mapped and surveyed strath terraces in the lower 3 km of the West Fork and determined minimum incision rates using radiocarbon dating of detrital charcoal and wood in basal alluvium on straths.

Nail Transects in Riverbed and Banks

We installed nails in the bed of the channel along three cross-channel transects spread throughout a 0.6-km-long stream reach (Fig. 2B; Table 1). We installed 76-mm-long masonry nails flush with the bed by drilling holes into the channel bed with a hammer drill and then pounding nails into the drilled holes. We surveyed a topographic profile between steel stakes hammered into banks as cross-section end points. We installed a nail every 0.5 m measured horizontally along a tape stretched between the monuments. We also installed nails in the bed at 1 m intervals in a line 1 m upstream from each transect, and at 1 m intervals in another line 1 m downstream from each transect. At cross-section 1, we drilled holes without installing nails, planning to measure hole depths over time, but abandoned the site after finding the holes filled with fine sediment. We used a caliper to measure nail exposure, to the nearest 0.01 in. (0.25 mm), on the nail's right-hand side facing upstream. Where our drilling chipped the rock, we measured outside of the chipped area. Upon remeasuring the nails in subsequent field visits, we noted if nails and the rock they had been embedded in had been eroded away, whether or not there was a trace of the drilled hole, and the hole depth. We measured the nail exposure annually from 1999 through 2003, and we noted whether nail heads had sheared or rusted off. We also measured nails in 2007 and 2011, but we found that either few nails remained (cross-sections 2 and 4) or that many nails had been sheared off (cross-section 3; Fig. 2B).

In the study reach, a seasonally wet high-flow channel varies in height above the perennially wet low-flow channel from a few decimeters to 1–2 m; the cross sections we chose are representative of this variability. We separately analyzed incision rates measured at nails in the perennially wet, low-flow channel from those in the high-flow channel, which is subject to seasonal wetting and drying. Cross-section 2 included a gravel bar and a bedrock bench partially covered by alluvium (Figs. 7A and 8A). Cross-section 3 included a strath terrace from which the river had stripped the alluvial mantle and a terrace riser (Figs. 7B and 8C); on the strath, we measured nail height above a sandy weathering residuum.

For a second, independent measure of bed lowering, we repeat-surveyed cross sections at the nail sites over a several-year period. Cross sections were initially surveyed with a hand level and tape; cross sections were resurveyed in 2007, 2011, and 2014 with an auto level. We could only reliably compare the resurveys at cross-section 2 because animal trampling had disturbed steel stakes at the other three cross sections.

We also installed nails in three bedrock banks (strath terrace risers; Table 1; Figs. 2B and 7C–7D). In a near-vertical bank 30 m downstream of cross-section 3 on the left bank (Fig. 7C), we pounded 127-mm-long (5 in.) nails without drilling holes into the friable rock, flush with the surface. In a sloping strath terrace riser at a second site downstream of cross-section 4 (Table 1; Fig. 7D), we predrilled holes and pounded in and measured 76-mm-long (3 in.) masonry nails in the same manner as in the riverbed transects. The third site is the portion of the nail transect along cross-section 3 extending above the active channel and onto the riser (Fig. 7B).

We calculated lowering as the difference in nail exposure between two measurements. Where nail heads had been rusted off between two measurements, we added the nail head thickness to the second measurement. We excluded nails that had been sheared off. Where nails had been bent, we measured along the bent nail. Where nails were missing and their absence could be confirmed as the result of bedrock erosion (e.g., no hole remained at the nail site), we used the nail length to calculate a minimum lowering. Where nails were missing, a hole remained, and the hole's depth could be measured, we used the hole depth to estimate bedrock lowering. We excluded measurements where the nail was missing but we could not determine with certainty that the nail had been removed along with the eroded bedrock, or where a hole was found but its depth could not be reliably measured.

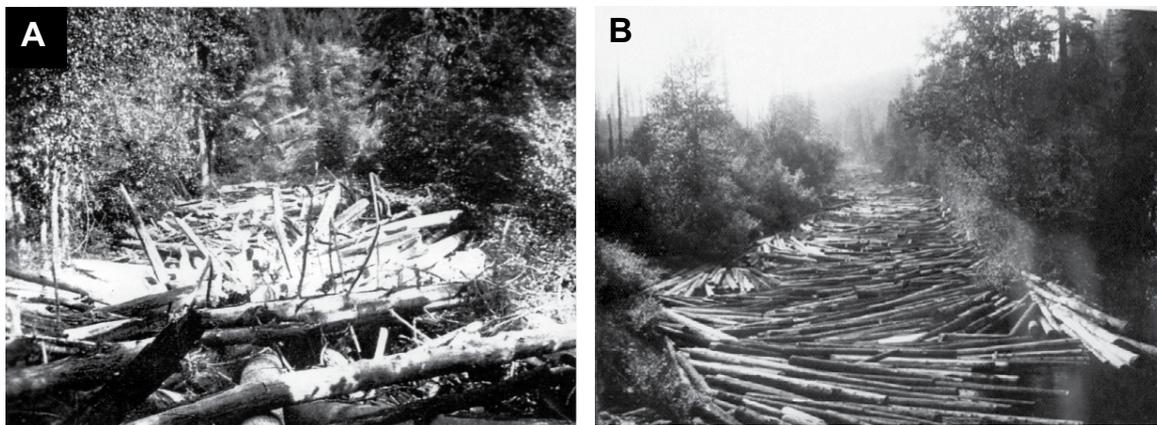


Figure 5. (A) Historical wood jam in the Middle Fork Teanaway River, from Russell (1898). Photo was likely taken in the period 1 April–30 June 1892 during Russell’s field work for a geological reconnaissance of the region (Russell, 1893). (B) Log drive in the main Teanaway River “ca. 1920.” Photo from the Frederick Krueger Collection, Central Washington University Library Archive, <http://digital.lib.cwu.edu/items/show/11687>.

Hydraulics of Bedrock and Alluvial Reaches

To characterize the spatial distribution of alluvial and bedrock reaches and relate it to sediment transport capacity, we first field mapped the occurrence of bedrock, alluvial,

and mixed bedrock-alluvial channel bed segments in the study reach (Fig. 3). We also surveyed a longitudinal profile of the thalweg and low-flow water surface using a total station, subdividing the surveyed profile at slope breaks and boundaries between alluvial, mixed, and bedrock channel bed segments, and determined

the average bankfull width for these subreaches from measurements in the field or from aerial photographs.

We then used the channel slope and width measurements averaged for our subreaches to compute basal shear stress as an index of sediment transport capacity. Most sediment

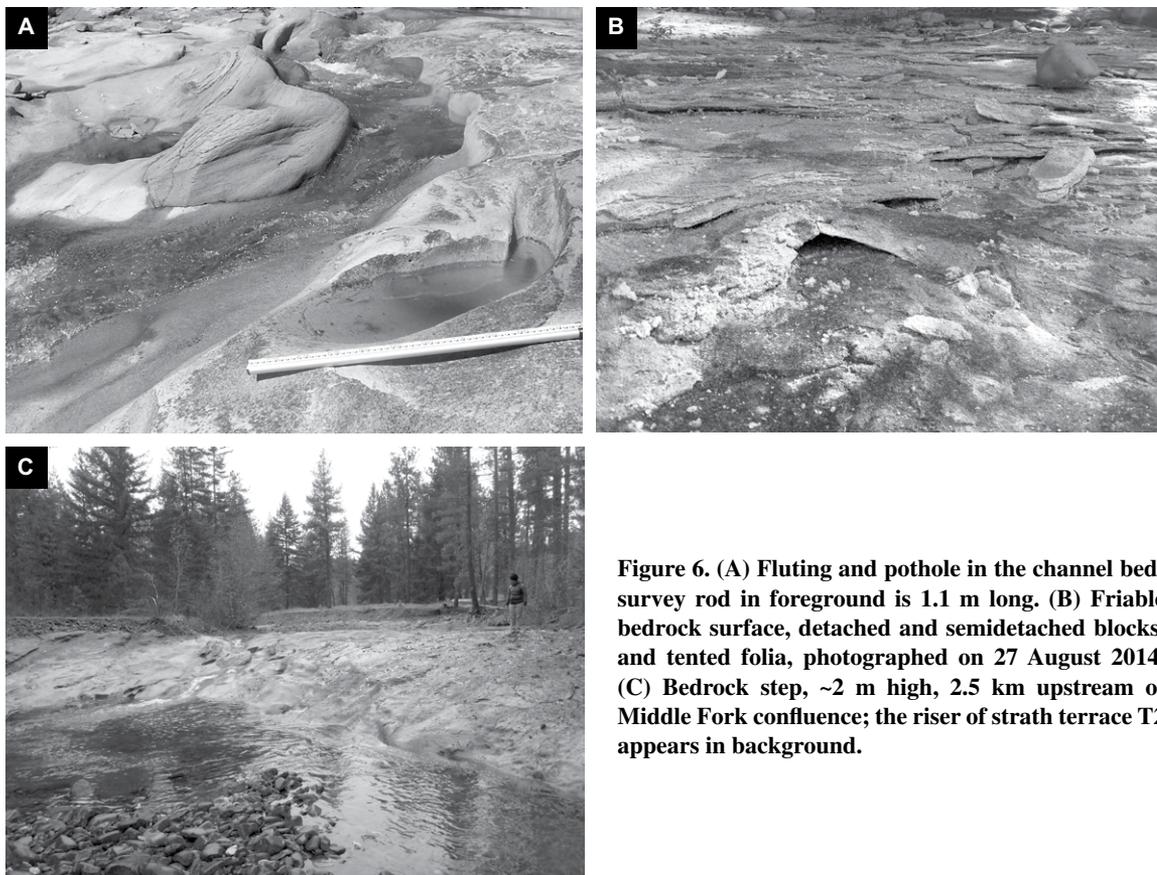


Figure 6. (A) Fluting and pothole in the channel bed; survey rod in foreground is 1.1 m long. (B) Friable bedrock surface, detached and semidetached blocks, and tented folia, photographed on 27 August 2014. (C) Bedrock step, ~2 m high, 2.5 km upstream of Middle Fork confluence; the riser of strath terrace T2 appears in background.

Bedrock incision and strath terrace formation in a forested catchment

TABLE 1. CHARACTERISTICS OF NAIL MEASUREMENT SITES

Site*	Number of nails	Nail spacing (m) [†]	Measurement period [§]	Transect length (m)	Bankfull width (m)
XS2	55	0.5–1.0	1999–2011	18.6	30.6
XS4	43	0.5	2000–2011	7.5	25.9
XS3	55	0.5–1.0	1999–2011	19.0 [#]	11.7
G1	4	NA	1999–2001	NA	NA
G2	62	1.0	2000–2011	NA	NA

*Drainage area ranges from 91.0 km² at site XS2 to 91.3 km² at site G1.

[†]Nails in cross-section 2 (XS2), XS3, and XS4 were installed in three lines with 1 m spacing between lines. Nails were spaced at 0.5 m in middle line; in XS2 and XS3, upstream and downstream lines were spaced at 1 m, and in XS4, lines were spaced at 0.5 m. Nails in G2 were in a regular grid at 1 m spacing, 4 × 13 m. Nails in G1 were in an irregular grid.

[§]Measured annually between 1999 and 2004, and then in 2007, 2011, and 2014.

[#]Nails along XS3 extended onto strath terrace riser and exposed strath surface.

transport equations relate sediment transport capacity to basal shear stress for steady and uniform flow:

$$\tau_b = \rho g h s, \quad (1)$$

where τ_b is the basal shear stress, ρ is the density of water, g is the acceleration due to gravity, h is water depth, and s is water surface slope. Because the bankfull flow is commonly taken as the geomorphically effective discharge, we computed shear stress for the bankfull discharge, which we approximated with the 1.5 yr

recurrence flow (Castro and Jackson, 2001), extrapolated for the study area from USGS gauge 12480000 (Figs. 1 and 4).

We developed a relationship between bankfull basal shear stress and measurable parameters using an approach similar to that used in previous field and modeling studies of bedrock channel erosion and strath formation (e.g., Hancock and Anderson, 2002; Snyder et al., 2003). We used our field-measured channel slope to approximate the water surface slope as the channel-bed slope. Flow depth for the bankfull discharge is given by:

$$h = \frac{Q}{u w}, \quad (2)$$

where h is the bankfull depth, Q is the bankfull discharge, u is average velocity at bankfull, and w is the bankfull width, in combination with the Manning equation:

$$u = \frac{h^{2/3} s^{1/2}}{n}, \quad (3)$$

where s is the channel slope, n is the Manning roughness coefficient, and flow depth, h , has been substituted for the hydraulic radius,



Figure 7. Nail measurement sites. (A) Nail transect 2, looking upstream. (B) Nail transect 3, looking downstream. (C) Nail grid 1, looking upstream. (D) Nail grid 2, looking upstream.

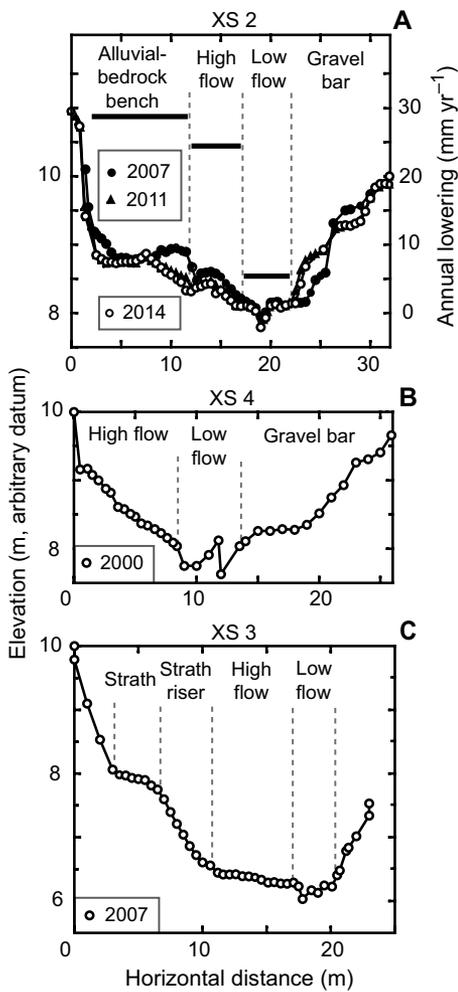


Figure 8. (A) Channel cross section (XS) surveyed in 2007, 2011, and 2014 along nail transect 2, and equivalent lowering (horizontal bars), in mm, in three portions of the cross section. (B) Channel cross section surveyed in 2000 along nail transect 4. (C) Channel cross section surveyed in 2007 at transect 3.

a common assumption for wide, shallow channels. Combining Equations 1, 2, and 3 produces the equation we used to compute boundary shear stress:

$$\tau_b = \rho g n^{0.6} \left(\frac{Q}{w} \right)^{0.6} s^{0.7}. \quad (4)$$

Straths and Valley-Fill Surfaces

We field-mapped strath terraces and measured their heights using a total station and laser range finder. We determined strath terrace height relative to the low-water surface as an appropriate measure of the average local channel elevation, uncomplicated by local channel

relief (Pazzaglia and Brandon, 2001; Wegmann and Pazzaglia, 2002). We correlated individual strath terraces from map and relative height relationships. We used aerial photographs, a global positioning system (GPS), and a total station survey to map valley-fill surfaces and a GPS to survey valley cross sections.

To estimate the age of strath-terrace alluvium, we sampled detrital charcoal, fir cones, and wood from the basal alluvium on straths, taking care to sample in situ, fluviually deposited materials rather than organic matter subsequently emplaced by tree roots (Wegmann and Pazzaglia, 2002). We assumed that the range in ages of detrital materials reflects the period when the strath was active, prior to strath abandonment and terrace formation (Personius et al., 1993; Merritts et al., 1994; Lavé and Avouac, 2000; Wegmann and Pazzaglia, 2002). Because the ages of detrital charcoal in alluvium can be older than the activity of channel deposits in which it is found due to the residence time in fluvial sediments of wood (e.g., Hyatt and Naiman, 2001; Montgomery and Abbe, 2006) or charcoal (e.g., Blong and Gillespie, 1978), we took the youngest of multiple ages from basal alluvium of a given strath as the maximum age at which the strath was abandoned.

We report ^{14}C ages as both conventional radiocarbon ages and as calibrated calendar yr A.D., as determined from the method of Stuiver and Reimer (1993) using the calibration curve by Reimer et al. (2013). Because all ages are late Holocene (≤ 1810 ^{14}C yr B.P.), most of our radiocarbon ages (10 of 15) return more than one calibrated age. We report the range of all 2σ ages having a $p > 0.25$. We computed a minimum incision rate as the height of the strath surface above the current low-flow water surface divided by the midpoint of the calibrated 2σ age range having the highest p value. Variability in stream-bed elevation can bias incision rates inferred from strath terraces (Gallen et al., 2015), but such an effect, if present, is probably small in the Teanaway River drainage because uplift rates are low, and alluvial cover is thin or absent.

RESULTS

Incision Rates and Processes

Visual observations along the study reach and each of the cross sections indicate that abrasion dominates erosion in the low-flow channel, whereas weathering and block removal dominate erosion in the high-flow channel. Bedrock in the low-flow channel is generally smooth and polished, with flutes and potholes common (e.g., Fig. 6A). In contrast, the high-flow surface is commonly rough and blocky, with blocks being

bounded by bedding planes and joints (e.g., Fig. 6B). Bedrock in the high-flow channel is heavily weathered. Tented folia, presumably the result of wetting-drying and freeze-thaw cycles, are common (Fig. 6B). Additionally, when viewed following seasonal exposure to wetting and drying cycles, the Roslyn Formation is soft, friable, and readily dissolved or broken by impact into constituent sand or silt grains (Fig. 6B). On annual visits to nail sites, we observed fresh exposures of bedrock where nails had previously been located, and no trace of the nails or the holes in which nails had been anchored, which supports our observations throughout the study reach that large blocks are detached and removed in the high-flow season. Impacts by bed-load particles, including particles up to ~ 0.5 m diameter, likely also loosen blocks. The fact that the active bed layer includes such exceptionally large particles, with diameters comparable to the bankfull flow depth, is presumably because of the enhanced mobility, and very low Shields numbers, of clasts on a smooth bedrock bed not lodged in alluvial patches (Costa, 1983; Hodge et al., 2011; Chatanantavet et al., 2013).

Measured lowering was generally greater in the seasonally wet high-flow channel than in the low-flow channel (Table 2; Fig. 9). In the high-flow channel, annual channel bed lowering at the three cross sections measured over four annual periods (1999–2003) averaged 10.9 mm yr^{-1} (range 0.8 – 30.6 mm yr^{-1} ; Table 2; Fig. 9A). At two of the cross sections (2 and 4), the low-flow channel lowered on average 3.8 mm yr^{-1} (range 1.2 – 6.6 mm yr^{-1} ; Fig. 9B), i.e., substantially less than lowering of the high-flow channels. These annual rates are minima because, over time in each cross section, some nails were lost where the bedrock in which the nails were anchored eroded away, and in these cases, we used the nail length to estimate a minimum vertical lowering; more nails were eroded away in the channel margin than in the channel thalweg (Table 2), and so lowering in channel margins would be more greatly underestimated than lowering in channel thalwegs. At cross-section 3, rates measured in the high- and low-flow channel did not significantly differ. The greater lowering at cross-sections 2 and 4 relative to cross-section 3 appears to stem from the high-flow surface having a greater height differential relative to the low-flow channel at cross-sections 2 and 4 compared to cross-section 3. Throughout the study reach, we found visual evidence of substantial weathering and erosion where the high-flow channel was from several decimeters to a meter higher than the low-flow channel. Average annual bed lowering across the entire cross section ranged between 1.0 mm yr^{-1} and 24.2 mm yr^{-1} , and averaged 9.5 mm yr^{-1} (Table 2).

Bedrock incision and strath terrace formation in a forested catchment

TABLE 2. VERTICAL LOWERING MEASURED AT NAILS AT THREE CHANNEL CROSS SECTIONS

Cross sections	Annual vertical lowering (mm)*											
	1999–2000			2000–2001			2001–2002			2002–2003		
	Mean	<i>n</i>	SE	Mean	<i>n</i>	SE	Mean	<i>n</i>	SE	Mean	<i>n</i>	SE
XS2												
All	15.5	45	2.1	2.8	57	1.7	20.7	45	3.4	9.0	29	3.4
Low flow	6.6	15	1.7	5.3	16	4.5	3.9	15	1.8	3.7	14	4.0
High flow	18.8	15	2.1	1.9	21	1.8	30.6	21	5.4	14.2	8	9.2
Mixed bedrock-alluvial bench	21.2	15	4.9	1.8	20	2.8	25.8	9	6.6	13.6	7	4.4
XS3												
All	4.2	48	0.8	1.0	49	0.6	3.0	39	0.7	2.9	39	0.7
Low flow	4.4	10	1.3	3.2	11	1.6	1.2	8	1.4	2.4	8	1.1
High flow	4.3	22	1.0	0.8	22	0.5	1.3	18	0.6	2.8	18	1.3
Strath terrace riser	4.1	16	1.9	-0.1	16	1.4	6.9	12	1.4	3.4	13	1.1
XS4												
High flow	NA	NA	NA	7.6	35	2.3	24.2	39	4.1	13.0	35	3.7

*Measurements were all made in low-flow season (August–November). “Low-flow” channel is the channel that remained wet throughout the low-flow season, and the “high-flow” channel is the remainder of the alluvium-free active channel; *n*—number of measurements; SE—standard error.

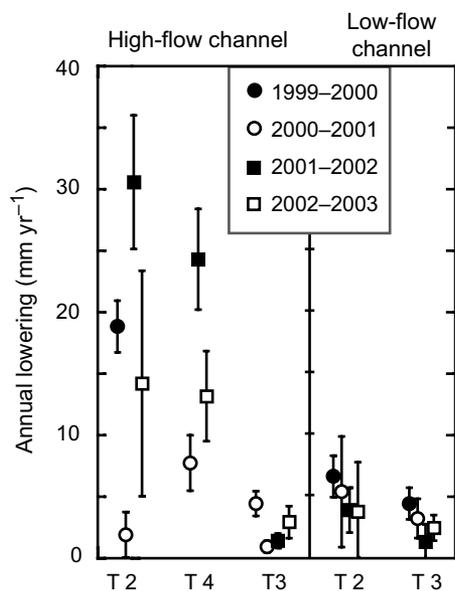


Figure 9. Mean annual vertical bed lowering at three nail transects, with one standard error of the mean, for the high-flow and low-flow channel. Data are from Table 2. T—transect.

to crack, shatter, and pulverize softened rocks by particle impacts, and to entrain materials created by these processes.

Lateral Erosion of Strath Terrace Risers

At two of the sites where we measured erosion of bedrock terrace risers relative to nails, annual erosion averaged 5.4 mm yr⁻¹ and 3.6 mm yr⁻¹ (Table 4). Our visual observations indicate rates are locally much higher than those measured at these two sites; this observation is confirmed by repeated measurement of nails installed in a grid on a third terrace riser (Fig. 7C), where backwearing averaged 21.8 mm yr⁻¹ (Table 4). These high rates are substantiated by the annual accumulation of piles of exfoliated bedrock sheets at the base of the terrace riser, and by exposed, undercut Douglas fir roots extending 1.3 m outward from the outcrop (Fig. 7C) from a tree aged with an increment borer as 90 yr. Surfaces at the other two sites had many tented and loosened folia (Fig. 7D), which presumably sloughed off due to snow-melt runoff, animal trampling, dry ravel, or surface erosion; thicker folia were shed parallel to the face on the steeper, third site. Average annual backwearing recorded at the three sites is 10.3 ± 5.8 mm yr⁻¹ (mean and standard error [SE], *n* = 3), taken as an average of the multi-year averages at the three sites, or 9.3 ± 0.6 mm yr⁻¹ (mean and SE, *n* = 10) if years at all sites are averaged separately.

Repeat topographic surveys at cross-section 2, from 2007 through 2014, substantiate the magnitude of incision rates and the difference in rate between the high-flow and low-flow channels (Table 3; Fig. 8A). Average annual lowering over the 7 yr period in the high-flow channel (24.8 mm yr⁻¹) was more than four times that in the low-flow channel (5.8 mm yr⁻¹); these rates and the differential between the high-flow and low-flow channels are similar to the minimum rates measured at nails on the same

transect from 1999 to 2003 (16.4 mm yr⁻¹ in the high-flow channel and 4.9 mm yr⁻¹ in the low-flow channel). The greater differential in rate between the high-flow and low-flow channels in the topographic survey compared to the differential recorded by the nail measurements may reflect the bias, described earlier, created by more nails having been eroded away in the high-flow channel than in the low-flow channel.

At the two more rapidly incising transects (cross-sections 2 and 4), annual incision in the high-flow channel correlates positively with peak annual flow (Fig. 10). In contrast, annual incision does not correlate with peak annual flow in the low-flow channel (Fig. 10). The dependence of annual incision on flow magnitude in the high-flow channel implies that incision magnitude is limited by processes operating in the high-flow season; subaerial weathering in the “preparation time” (Hancock et al., 1998) between high-flow events would loosen blocks, create folia, and disaggregate particles, and subsequent incision would be limited by the efficacy of high flows to quarry and detach blocks,

TABLE 3. VERTICAL LOWERING OF THE CHANNEL BED AT CROSS-SECTION 2 MEASURED BY REPEAT LEVELLING

	Cross-section topographic survey				Nails	
	2007–2011		2011–2014		2007–2014	1999–2003
	(mm)	(mm yr ⁻¹)	(mm)	(mm yr ⁻¹)	(mm yr ⁻¹)	(mm yr ⁻¹)*
All	131.8	32.9	19.7	6.6	21.6	12.0
High flow	146.4	36.6	26.9	9.0	24.8	18.2
Low flow	24.7	6.2	16.1	5.4	5.8	4.9
Mixed bedrock-alluvial bench	180.9	45.2	17.8	5.9	28.4	15.6

*For comparison with cross-section lowering, column shows average annual lowering measured relative to nails, 1999–2003 (from Table 2).

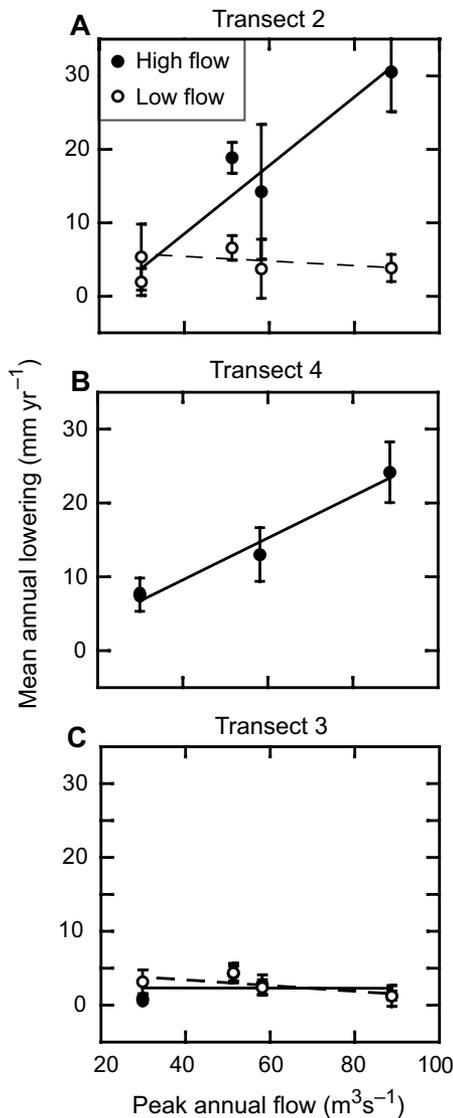


Figure 10. Peak annual flow, from Figure 2, against average annual lowering, 1999–2003, from Table 2, at nail transect 2 (A), transect 4 (B), and transect 3 (C). Lowering is shown separately for the high-flow (solid symbols) and low-flow (open symbols) channels. Error bars are one standard error.

only modestly greater than that of alluvial reaches; median values are comparable (0.0106 and 0.0107, respectively); the average slope of bedrock reaches is greater than that of alluvial reaches (0.024 and 0.011, respectively) because of several steep sections of bedrock (Fig. 11A). However, the bankfull channel is generally narrower in bedrock sections than alluvial sections (median of 13.5 and 21.2 m, and mean of 13.7 and 22.4 m; Fig. 11B). Narrower reaches are associated with channel confinement by strath terraces along one or both channel banks (Fig. 11B), and consequently a greater bankfull shear stress (Fig. 11C). We calculated bankfull shear stress (see Eq. 4) using a single value for Manning’s *n* roughness (0.04) throughout the study reach because we lacked a quantitative basis for assigning different roughness coefficients for bedrock and alluvial reaches. However, Goode and Wohl (2010) measured high roughness values (Manning’s *n* = 0.059–0.094) in a bedrock river having longitudinal and oblique bedrock ribs that appear to be of similar scale to the ribs and flutes in the West Fork Teanaway River, suggesting roughness, and consequently flow depth and shear stress, may be even greater in our bedrock reaches than indicated in Figures 11B and 11C.

Wood is uncommon in the 3-km-long study reach and plays a small role in controlling the deposition of sediment. In a 2012 inventory, we counted only 18 pieces >10 cm in diameter and >2.0 m in length (9 individual pieces and 1 jam of 9 pieces) in the 3 km study reach, or 6 pieces km⁻¹ and 0.3 jams km⁻¹. For comparison, in streams elsewhere in the Yakima River drainage that lack historical wood removal or riparian logging, fluvial wood in a 1990–1992 field sur-

vey averaged 61.8 pieces km⁻¹, with 11.3 jams km⁻¹ (McIntosh et al., 1994). Each of the large pieces and the jam we observed was associated with the deposition of gravel bars.

Strath Terrace Distribution and Incision Rates

Strath terraces are visible along the river from its mouth to river kilometer (RK) 3, upstream of which no terraces are evident (Fig. 12A), and the main valley-fill surface is the same as, or only slightly higher than, the floodplain (Fig. 3A). Strath heights along the river range from 0.1 m to 5.5 m; while strath heights in a subreach are highly variable, the maximum height above the riverbed increases upstream to a maximum of 5.5 m at about RK 1.8 and then decreases upstream to the farthest upstream-occurring strath at RK 3 (Fig. 12B). Straths are unpaired, and their height above the low-flow channel can vary considerably longitudinally along continuously exposed straths (indicated by connected points in Figs. 12A and 12B). Some of this strath-surface topography is associated with what appear in the field to be relict bedrock channels inset into the strath surface.

Radiocarbon dates of sampled organic matter in basal alluvium along the West Fork Teanaway River range between 40 ± 30 yr B.P. and 1810 ± 40 yr B.P. (±1σ; Table 5). Incision rates, calculated from calendar ages for these samples as described previously, range between 0.3 mm yr⁻¹ and 13.7 mm yr⁻¹ and average 3.3 mm yr⁻¹. We identified three terrace treads in the field; incision rates calculated from samples from alluvium of the two highest surfaces, T3 and T2, average 1.3 ± 0.3 mm yr⁻¹ and 1.4 ± 0.5 mm yr⁻¹, respectively, and 7.4 ± 3.6 mm yr⁻¹ for T1, the lowest surface (mean and standard error; Table 6).

Radiocarbon ages of samples from the older two surfaces span a substantial range: Average ages of samples in the higher (T3) surface span ~460 yr (A.D. 375–830), those from the middle surface (T2) span ~840 yr (A.D. 718–1561), and ages from the lowest surface (T1) span ~30 yr (A.D. 1866–1893; Fig. 13). These age ranges

Longitudinal Variation in Alluvial Cover and Bankfull Shear Stress

Counter to the expectation that reaches in which bedrock is exposed would be steeper than those in which the bed is covered by alluvium, the field-measured channel slope of stream reaches having exposed bedrock was

TABLE 4. ANNUAL LATERAL INCISION, IN mm, MEASURED RELATIVE TO NAILS IN STRATH TERRACE RISERS

Site*	Annual incision (mm)												Average annual incision (mm) [§]		
	1999–2000			2000–2001			2001–2002			2002–2003			Mean	<i>n</i>	SE
	Mean	<i>n</i> [†]	SE [†]	Mean	<i>n</i>	SE	Mean	<i>n</i>	SE	Mean	<i>n</i>	SE			
G2	NA	NA	NA	3.0	62	0.6	9.4	62	1.5	3.8	62	2.1	5.4	3	2.0
XS3	4.1	16	1.9	-0.1	16	1.4	6.9	12	1.4	3.4	13	1.1	3.6	4	2.9
G1	15.3	4	4.9	3.0	4	5.7	47.2	4	23.7	NA	NA	NA	21.9	3	13.2

*Two nail installations were made as grids (G1 and G2); the third is the part of a transect (cross-section 3 [XS3]) that falls on a strath terrace riser. Measurements were made during the period from August to November.

[†]*n*—number of measurements, SE—standard error.

[§]Column shows the average of all years at each site.

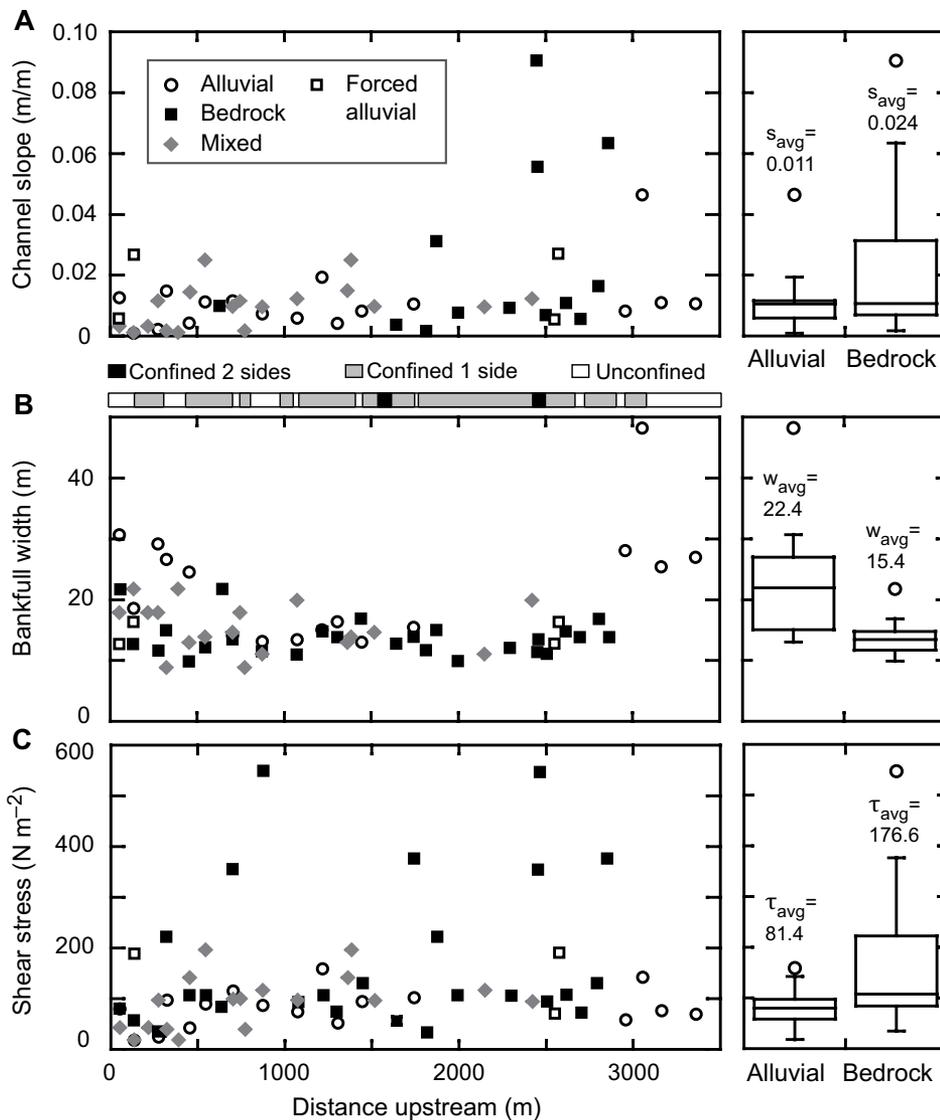


Figure 11. (A) Variation in channel slope in the West Fork Teanaway River study area for alluvial, bedrock, and mixed alluvial-bedrock segments. Occurrence of alluvium and bedrock is from field mapping in 2012, and bed slope is from a 2013 total station survey. (B) Variation of the bankfull width and (C) modeled bankfull shear stress for the same segments, calculated as described in the text and assumed an unvarying value for the Manning’s n roughness coefficient ($n = 0.04$). Boxes in right-hand panels enclose 50% of the data, with the median value displayed as a line. The lines extending from the top and bottom of each box indicate the minimum and maximum values, excepting outliers (circles), or points with values greater than the inner quartile plus 1.5 times the inner two quartiles. s_{avg} , w_{avg} , and τ_{avg} in right-hand panels refer to average slope, width, and shear stress, respectively.

could indicate the period of time over which terrace abandonment occurred throughout the reach; alternatively, the age ranges could also reflect the residence time of the charcoal in the fluvial system prior to strath abandonment. The overlap in ages of samples from T3 and T2 (sample 1 in Fig. 13) would be consistent with rapid incision upon abandonment of the T3 surface. Alternatively, it is possible that, given

the lack of continuous strath exposures in this downstream portion of the study area, the T2 tread is developed on the T3 strath.

If we assume abandonment of each surface occurred over a short time period and approximate the maximum strath abandonment age by the respective minimum radiocarbon age from each surface, abandonment would have been complete at ca. A.D. 830, A.D. 1560, and A.D.

1890 for T3, T2, and T1, respectively (Fig. 13). Surface-averaged incision rates calculated making this assumption are more rapid than those calculated by simply averaging all dates from each surface, especially for the middle terrace (T2), but the difference in rates calculated using the two different sets of assumptions is not great or statistically significant (Table 6).

Strath terraces in the main-stem Teanaway River valley are small and isolated, and we did not systematically map them. However, ages of samples from the basal alluvium of two main-stem Teanaway River strath terraces we sampled are consistent with the ages of samples from higher and middle surfaces in the West Fork Teanaway River, T3 and T2 (Fig. 13). In addition, the relative heights of the two sampled surfaces (4.6 and 3.3 m, respectively; Table 5) are consistent with the possibility that main-stem and West Fork Teanaway strath terraces are correlated.

A comparison of contemporary bed and bank incision rates directly measured relative to nails or by cross sections with incision rates calculated from strath terraces shows that rates are greatest for the high-flow channel, as determined from nails and repeated topographic survey, and that these rapid rates are comparable to rates of bedrock terrace riser backwearing measured by nails and to the calculated incision rate of the lowest strath terrace (Fig. 14). Rates are less for the low-flow channel, as measured by nails and cross sections, and least for the higher two straths (T2 and T3). The alternative calculation of strath terrace incision rate using the maximum abandonment age, described earlier, does not affect these groupings (Fig. 14).

DISCUSSION

In this section, we draw from our results to explore, in order: how erosional processes and weathering interact to effect greater rates of vertical incision in channel margins than thalwegs; how this cross-channel differential in process and rate could result in rapid lateral bedrock planation and strath formation; how relatively rapid lateral bedrock erosion might, in turn, internally limit vertical incision; and the potential role of fluvial wood in mediating vertical incision.

Cross-Channel Variability in Processes and Rates of Bedrock Incision

Vertical incision rates measured by nail transects and repeated topographic survey in the study area are rapid; compared to reported rates (see compilation by Lamb et al., 2015), they are exceeded only by incision at an artificially created knickpoint (Johnson et al., 2010), from

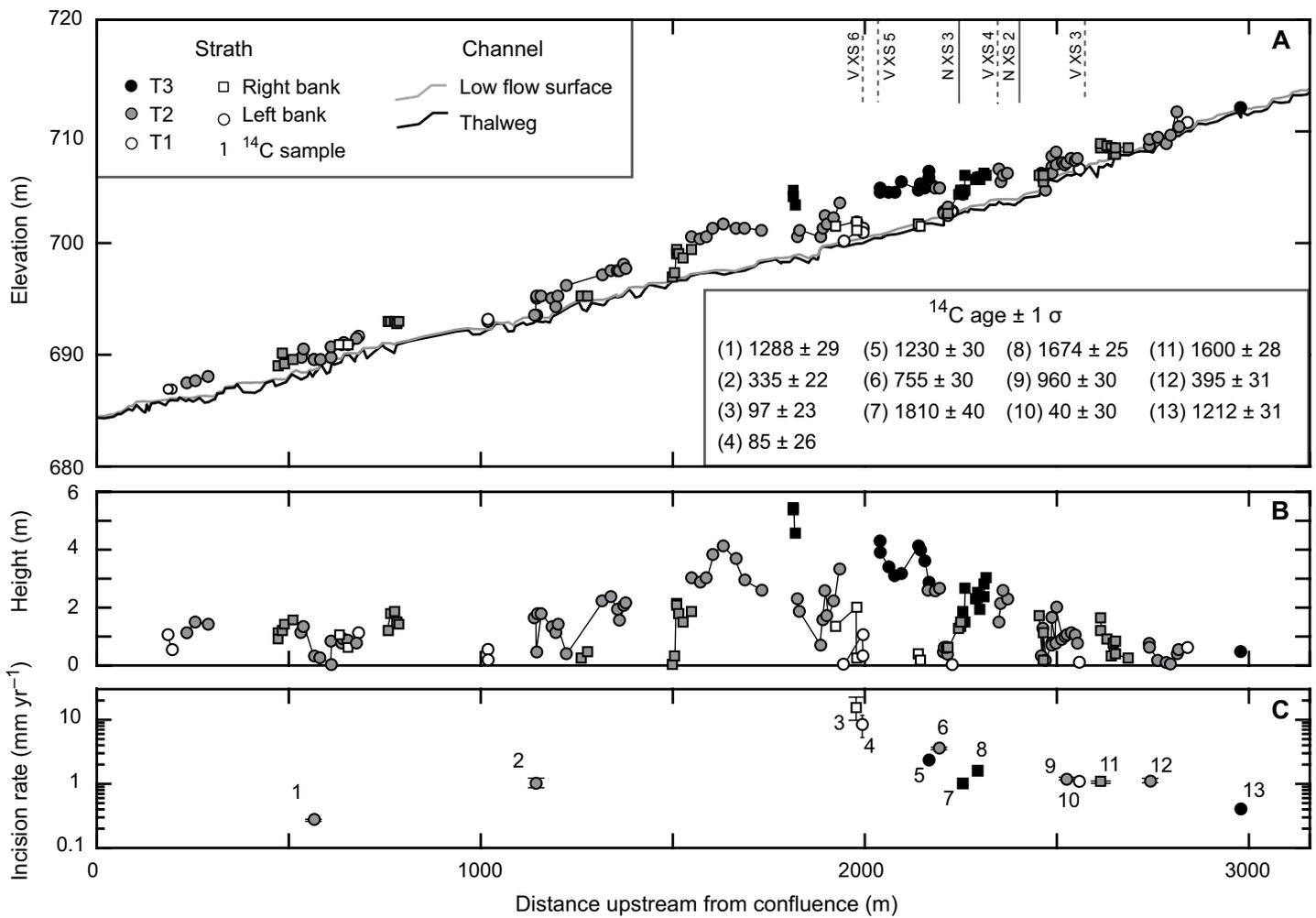


Figure 12. (A) Longitudinal profile of the channel thalweg, water surface, and strath surfaces, surveyed with a total station in 2013. Lines connecting surveyed strath locations represent field-confirmed continuous surfaces. North-bank (left bank) and south-bank (right bank) straths are shown separately. Dashed lines at top of panel (“VXS”) are locations of valley cross sections (Figs. 2 and 3), and solid lines (“NXS”) are locations of nail transects (Figs. 2 and 8). Nail transect 4, not shown, is 13 m downstream of transect 2. (B) Height of strath above low-flow water surface, in meters. (C) Minimum bedrock incision calculated as strath height above low-flow water surface divided by the number of calendar years between the midpoint of the 2σ bounds of calibrated calendar age of radiocarbon-dated material in basal alluvium (Table 5) and the year in which strath heights were field measured.

large floods (Hartshorn et al., 2002; Lamb and Fonstad, 2010), or at knickpoints created by sudden fault rupture in weak mudstone and siltstone (Cook et al., 2013). The rapid rate we measured over a several-year period is likely representative of at least the last several decades: The measurement period lacked unusually large storms (Fig. 4), and the measured rate is similar to the century-scale incision rate implied by the lowest strath terrace (Fig. 14).

Our visual observations, from throughout the study area, and supported by measurements from a limited number of sites, indicate that rates are greatest where a bedrock bench is elevated above the low-flow channel, and that subaerial weathering promotes this more rapid rate. Weathering favors formation, loosening,

and disintegration of blocks into pieces that can be removed by high flows, as observed in a shale-bed river by Tinkler and Parish (1998). Weathering also increases rock susceptibility to bed-load particle impacts, crushing and breaking rock so that it can be plucked or entrained, as observed for mudstones and siltstones by Cook et al. (2013). We presume that seasonal wetting and drying of rock above the annual minimum water table is the dominant weathering mechanism; this is analogous to those coastal terraces from which waves remove weathered material produced above the discontinuity in rock strength imposed by the water table (Retallack and Roering, 2012).

These cross-channel differences in incision rate and processes confirm previous labora-

tory experiments: In abrasion mill experiments conducted by Small et al. (2015), rocks from channel margins eroded more rapidly than rocks from the channel thalweg, a difference Small et al. (2015) attributed to the greater weathering depth in the channel-margin rock samples relative to the low-flow samples. However, the fact that we measured greater rates of vertical incision in channel margins than channel thalwegs contradicts the hypothesis that channel margins and thalwegs incise at the same rate; rather, it appears that incision rate is unsteady in channel margins, where transiently high, weathering-promoted rates likely persist until channel-margin incision evens out variations in cross-channel elevations. Our field measurements also show that annual peak flow magnitude correlates

Bedrock incision and strath terrace formation in a forested catchment

TABLE 5. RADIOCARBON AGES OF SAMPLES FROM BASAL ALLUVIUM ON STRATH TERRACES AND ASSOCIATED MINIMUM INCISION RATES

Distance upstream from MF confluence (km)	Strath terrace ID	#*	Field sample ID	Lab sample ID [†]	Strath height [§] (m)	¹⁴ C age (yr B.P. ± 1σ)	Calibrated 2σ age range [¶] , yr A.D., and relative area under distribution	Minimum incision rate (mm yr ⁻¹)**
West Fork Teanaway River								
0.58	T2	1	10-18-12-1	D-AMS-003711	0.35	1288 ± 29	666–769 (1.00)	0.26–0.28
1.14	T2	2	10-18-12-3	D-AMS-003709	0.46	335 ± 22	1482–1639 (1.00)	0.87–1.23
1.97	T1	3	8-27-14-6	D-AMS-008578	2.0	97 ± 23	1810–1925 (0.73) 1690–1729 (0.27)	9.80–22.47
1.98	T1	4	10-18-12-4	D-AMS-003712	1.07	85 ± 26	1810–1922 (0.74) 1691–1729 (0.26)	5.30–11.89
2.15	T3	5	10-25-11-6	B309426	2.87	1230 ± 30	760–882 (0.66) 689–751 (0.34)	2.29–2.54
2.17	T2	6	10-7-12-6	D-AMS-003708	2.71	755 ± 30	1222–1284 (1.00)	3.43–3.72
2.24	T3	7	10-25-11-5	B309424	1.85	1810 ± 40	122–265 (0.82)	0.98–1.06
2.28	T3	8	10-7-12-5	D-AMS-003706	2.55	1674 ± 25	329–420 (0.97)	1.52–1.60
2.52	T2	9	10-25-11-4	B309425	1.09	960 ± 30	1063–1154 (0.69) 1021–1059 (0.32)	1.15–1.27
2.54	T1	10	10-25-11-2	B309423	0.14	40 ± 30	1867–1919 (0.56) 1695–1728 (0.21)	0.97–1.25
2.61	T3	11	10-7-12-4	D-AMS-003707	1.64	1600 ± 28	402–537 (1.00)	1.02–1.11
2.81	T2	12	8-27-14-7	D-AMS-008577	0.60	395 ± 31	1438–1523 (0.75)	1.04–1.22
2.98	T3	13	10-7-12-3	D-AMS-003710	0.48	1212 ± 31	763–890 (0.85)	0.38–0.43
Teanaway River								
NA	NA	a	8-27-14-2	D-AMS-008579	4.6	1247 ± 24	680–778 (0.83)	5.53–5.86
NA	NA	b	8-27-14-5	D-AMS-008580	3.3	467 ± 24	1417–1451 (1.00)	3.45–3.72

Note: All dated materials were detrital charcoal except for sample 11, which was a fir cone. MF—Middle Fork.

*#1–13 refers to sample site numbering used in Figs. 12 and 13; location of main-stem samples a and b are shown in Figure 1.

[†]Lab ID assigned at dating laboratory: B—Beta Analytic Inc., Coral Gables, Florida; D-AMS—Direct AMS, Seattle, Washington. All ages are from accelerator mass spectrometry.

[§]Strath height is relative to low-flow water surface.

[¶]2σ range for calibrated ages (yr B.P.) determined from method by Stuiver and Reimer (1993) using calibration curve by Reimer et al. (2013); ranges are reported for all peaks with $p > 0.25$.

**Incision rate was calculated using calibrated age 2σ ranges from previous column, using most probable age range (highest p value). Range of p values used is: $0.69 < p \leq 1.0$.

with lowering depth in the weathering-dominant portion of the channel (Fig. 10), suggesting that, at least in a period with no extreme flow events (Fig. 4), lowering in the weathering-dominated channel margins is limited by the rate at which high flows can scour weathered material. This cross-channel differential in erosion processes and rates also suggests a mechanism by which rivers might accomplish rapid lateral planation of straths, as discussed next.

Mechanism for Rapid Vertical and Lateral Incision

Whereas we measured high annual rates of lateral erosion of strath terrace risers (Fig. 14), averaging 10.3 mm yr⁻¹ and as rapid as 47 mm yr⁻¹, these rates are still an order of magnitude lower than the lateral planation rate that is implied by the distance between bedrock risers in

the field area. For example, using the horizontal distance between risers for terrace T3 across the large meander crossed by valley transects 5 and 6 (Figs. 2 and 3) and the range of terrace abandonment dates from Table 5, we find a lateral incision rate since strath abandonment of ~90–140 mm yr⁻¹. This requires a different mechanism to explain lateral planation in addition to simple lateral incision of exposed bedrock.

Rapid vertical incision of the high-flow channel, in combination with stripping of floodplain alluvium by lateral channel erosion, could provide a mechanism for rapid lateral channel movement and terrace retreat. During high flows, lateral channel erosion can remove the alluvial cover from the adjacent floodplain atop an incipient strath terrace; such stripping of alluvium would expose the bedrock surface and subject it to weathering and potential scour during high flows (Fig. 15). The field area

includes a number of strath surfaces from which the alluvial mantle has been stripped away, and which are generally higher than bankfull stage but low enough to be subject to scour and periodic vertical incision during the highest flows. An example is along cross-section 3 (Figs. 7B and 8C); here, our nail transects installed in 1999 extended up onto the exposed strath surface, which in 1999 was covered by an accumulation of grus-like disaggregated sand particles. We installed nails flush with the weathered sand surface, which remained unchanged through the summer 2003 measurement. However, at the time of our 2007 measurement, which followed a flow that exceeded the 10 yr recurrence (Fig. 4), the weathered sand had been removed, and the remaining nails were either missing, sheared off, or exposed up to 31 mm.

This “top-down” mechanism for rapid bedrock channel widening through vertical incision

TABLE 6. AVERAGE INCISION RATES FOR STRATH TERRACES INFERRED FROM AGE OF BASAL ALLUVIUM AND FROM ESTIMATED MAXIMUM ABANDONMENT AGE

Strath terrace ID	Sample size	Average incision rate from radiocarbon sample ages* (mm yr ⁻¹)			Average incision rate, from surface abandonment age [†] (mm yr ⁻¹)		
		Mean lowering (mm yr ⁻¹)	Standard error (mm yr ⁻¹)	Median (mm yr ⁻¹)	Mean lowering (mm yr ⁻¹)	Standard error (mm yr ⁻¹)	Median (mm yr ⁻¹)
T3	5	1.3	0.3	1.1	1.6	0.4	1.6
T2	5	1.4	0.5	1.1	2.3	0.9	1.3
T1	3	7.4	3.6	7.3	8.9	4.4	9.0

*Incision rates calculated from calibrated age of radiocarbon samples in basal alluvium listed in “minimum incision rate” column, Table 5.

[†]Incision rates calculated using “maximum abandonment age,” from Fig. 13.

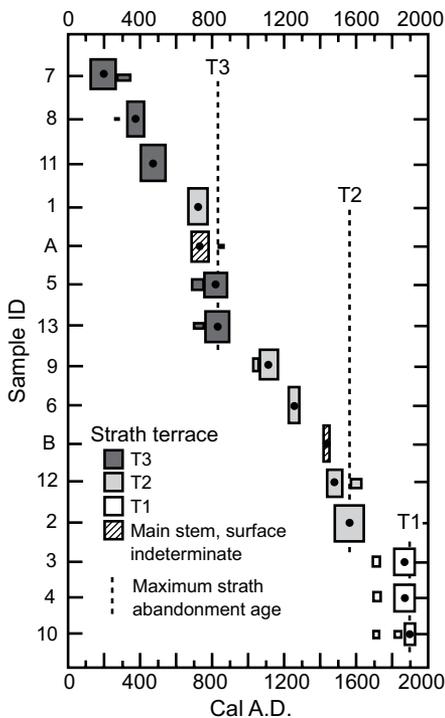


Figure 13. Calendar ages of radiocarbon-dated materials in basal alluvium on straths, arranged by surface (see Fig. 2). Multiple boxes for an individual sample represent multiple possible radiocarbon dates; height of box represents the relative area under the probability distribution for the age range enclosed by the box. Numbers on left-hand side refer to sample identification in Table 5 and Figure 12C.

could account for the lateral incision that accompanied the West Fork Teanaway River's outward migration at the large meander described earlier (Fig. 3). For example, a high-flow event or events might strip the alluvial cover on the stream's outer bank from a 10 m width (roughly one half of a channel width) of a low strath terrace (Fig. 15). Assuming a lateral incision rate of 0.01 m yr^{-1} and no vertical incision of the newly exposed bedrock, the 10-m-wide bedrock bench would be removed in 1000 yr. Instead, if the newly exposed rock were incised vertically at 0.01 m yr^{-1} via removal of subaerially weathered bedrock by high flows, a low terrace 0.5 m high would be removed in only 50 yr, an effective lateral planation rate of 0.2 m yr^{-1} . This could happen as long as the abandoned strath can be scoured by large floods. In the West Fork, the height of flood scour is at least 2 m above the thalweg; the strath surface at cross-section 3 is 2 m above the low-flow channel (Fig. 8C) where we observed fluvial stripping of weathered rock by a moderately high (between 10 yr

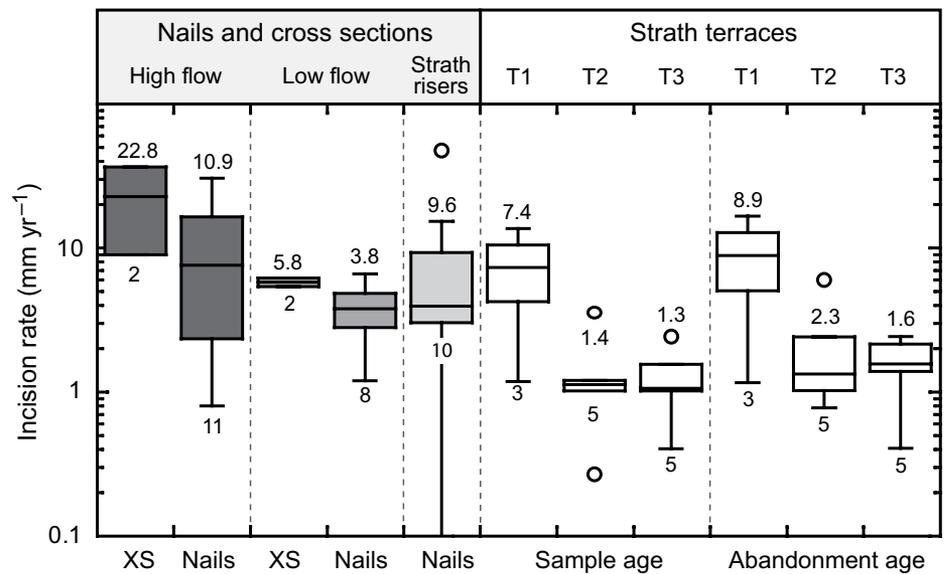


Figure 14. Bedrock incision rates compared to incision rates calculated from strath terraces. Annual bedrock incision rates (1999–2000, 2000–2001, 2001–2002, and 2002–2003), in mm yr^{-1} , are from field-measured nail transects (from Table 2); average annual bedrock incision rates, in mm yr^{-1} , are from repeated topographic survey, 2007–2011 and 2011–2014, of cross sections at nail transects (from Table 3); and annual bedrock erosion along bedrock terrace risers (1999–20002, 2000–2001, 2001–2002, 2002–2003), in mm yr^{-1} (from Table 4) is also given. Minimum incision rates implied by radiocarbon-dated materials (from Table 5) in basal alluvium resting on straths associated with three terrace levels in the West Fork Teanaway River valley were calculated using the calendar age of samples and using the maximum strath abandonment age, from Figure 13, as described in text. Boxes and vertical lines are as described for Figure 11; numbers above boxes are mean; numbers below are sample size. XS—cross section.

and 25 yr recurrence) flow, indicating vertical erosion following alluvium stripping is a viable mechanism for channel widening.

Recently, Johnson and Finnegan (2015) reviewed topographic evidence and argued that bedrock rivers can migrate laterally, and they described a field example of a bedrock channel in which cycles of wetting and drying enhanced lateral erosion at the outside of bends in a mudstone in the Santa Cruz Mountains, California. The mechanism we describe would also result in enhanced lateral erosion at the outside of bends and would favor bedrock meander development, as observed in the West Fork Teanaway River (Fig. 2B).

Internal Limit to Vertical Incision by Adjustment to Channel Geometry

Unsteadiness in vertical incision determined from a topographic record of strath terraces follows logically from the sequence through which such terraces are formed: Terraces result from periods of vertical incision alternating with incisional hiatuses in which widening dominates, and average incision rates estimated from

strath terraces necessarily integrate rates over both parts of the cycle. That vertical and lateral incision alternate in a cycle implies that average incision rates estimated from straths can be biased, depending on when measurements are made in a downcutting and subsequent widening cycle. For example, average incision rates implied by straths in the West Fork Teanaway River are indistinguishable for the middle (T2) and upper (T3) straths (Table 6; Fig. 14), but the rate implied by the lowest strath (T1) is greater; this could be because the lowest strath terrace is still in the vertical incision phase, and the measurement period (from onset of strath abandonment to the present) does not include an incisional hiatus—a widening-dominated part of the terrace-forming cycle. This inference is supported by the century-scale incision rate recorded by the lowest (T1) terrace being comparable to the instantaneous, annual-scale rates measured relative to nails (Fig. 14).

The causes of incisional hiatuses—transition from dominance of vertical to horizontal incision—are generally interpreted as a response to external drivers: an unsteady sediment or water supply, unsteady uplift, or transient upstream

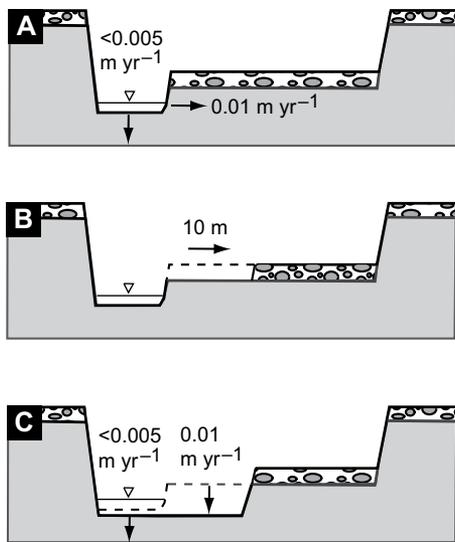
Bedrock incision and strath terrace formation in a forested catchment

Figure 15. Hypothesized conceptual model for rapid lateral strath planation. (A) Measured rates of lateral bedrock planation and strath formation are 0.01 m yr^{-1} , and low-flow channel vertical incision is 0.005 m yr^{-1} ; in the presence of a thick alluvial cover, this rate would be lower. (B) Lateral planation can proceed at a much faster rate where high-flow events scour and remove the alluvial cover from low strath terraces or incipient terraces, exposing the bedrock to subaerial weathering and subsequent detachment by high-flow events, measured as 0.01 m yr^{-1} . (C) The lateral planation rate is limited by the vertical high-flow channel incision rate, and the height and width of the terrace; if a 1-m-high terrace is stripped of its alluvial cover over a 10 m width, in the simplest case of no vertical incision in the low-flow channel, lateral planation of 11 m would be complete in 100 yr for a lateral incision rate of 0.1 m yr^{-1} .

propagation of a knickpoint from downstream base-level fall. These external drivers can effect change to channel geometry that in turn increases vertical incision; for example, in response to rock uplift, in addition to steepening, channels may narrow by increasing local incision rate (Finnegan et al., 2005; Whittaker et al., 2007). However, in rivers such as the Teanaway River that are not subject to rapid uplift or active faulting, incisional hiatuses must be triggered by change to a different external driver, such as sediment supply, or by an internal mechanism.

The duration of rapid vertical incision could be internally limited by changes to the relative importance of vertical and horizontal erosion throughout an incisional episode. Once incision is initiated, channel narrowing causes

shear stresses to increase, leading to efficient conveyance of sediment through the reach, and hence this may maintain exposed bedrock in the streambed that can be incised much more rapidly than a bed covered with alluvium. However, if bedrock channels can widen rapidly, incision rates should decline with time as the channel widens, shear stresses decline, and alluvial cover increases.

Observations of channel width and alluvial cover in the actively incising bedrock zone in the West Fork Teanaway River are consistent with such a model. Locally high shear stress and an associated absence of alluvial bed cover are maintained more by channel narrowing due to lateral confinement by bedrock terrace risers than by channel steepening (Fig. 11). This could be because in rapidly incising reaches, not enough time has elapsed for bedrock terrace risers to have receded and for channels to have widened. The observation that the alluvial reach downstream from the actively incising bedrock reach is generally wider and less confined by straths (Fig. 11) could reflect widening following passage of the rapidly incising zone. The downstream alluvial reach is $\sim 10\text{ m}$ wider than the actively incising reach (Fig. 11B); this corresponds to $\sim 100\text{--}1000\text{ yr}$ of lateral erosion, with the higher number predicted by our nail measurements of exposed strath terrace risers (on average 10 mm yr^{-1} or $10\text{ m}/1000\text{ yr}$), and the lower number hypothesized from the rapid lateral incision mechanism described earlier.

The fact that the actively incising reach of the West Fork Teanaway River is not steeper than the upstream or downstream reaches is inconsistent with the common association of locally rapid incision with knick zones—steepened sections of a bedrock channel profile—which have been observed to migrate upstream from a base-level fall (Bishop et al., 2005; Crosby and Whipple, 2006; Berlin and Anderson, 2007), or to initiate in steeper, smaller-drainage-area parts of a drainage (Crosby and Whipple, 2006), or in response to local uplift (Finnegan et al., 2005). It suggests, instead, that locally rapid incision could be maintained by channel narrowing associated with incision, but that such rapid incision is inherently temporally limited because the channel will widen due to backwearing of exposed bedrock banks and low straths. Such an internal limitation on rapid incision should be most effective in locations where strath heights are lower than the height of extreme flood events that could strip away the alluvium on strath surfaces, because it is in these locations where the channel could widen most rapidly by the stripping of strath-mantling alluvium, exposing the strath surface to weathering and vertical incision.

Loss of Fluvial Wood as a Cause of Historic Incision

While we lack direct evidence for the triggers of incisional episodes or incisional hiatuses, the coincidence in time between what was likely sudden and complete wood removal by log drives using splash dams and abandonment of the lowest strath (Table 5; Fig. 13) is strong circumstantial evidence that late-nineteenth-century wood clearing, and possibly erosional effects of splash damming itself, triggered incision by removing alluvium-storing wood accumulations, which would have increased the amount of subaerial-exposed bedrock in the channel. We lack direct evidence of wood loads in the Teanaway River prior to Euro-American settlement in the late nineteenth century, but field surveys of wood in nearby, protected watersheds cited previously (McIntosh et al., 1994) and observations in the adjoining Middle Fork Teanaway River by Russell (1898) strongly suggest that wood loads in the West Fork Teanaway River were much greater prior to late-nineteenth-century splash damming and logging. Bedrock incision could also further limit wood recruitment (and thus retention of alluvium) by initiating a positive feedback: Lateral channel bank erosion is a dominant mechanism for recruiting wood in unconfined alluvial streams (e.g., Latterell and Naiman, 2007), and a stream's incision into bedrock would transform it into a bedrock-confined channel without the capacity to laterally erode alluvium and recruit streamside trees.

If this inference is correct, more generally, the relative abundance of in-channel wood, through its role in retaining alluvium on the channel bed, could be a dominant control on the initiation or duration of periods of vertical incision. Controls on the supply of in-channel wood include the amount, species, and size of wood associated with different forest types, as well as fire regimes, and landslide delivery of wood to headwater channels, all of which are at least partially related to climate. Climatic and other controls on the relative supply of fluvial wood capable of retaining bed sediment should thus be considered as potentially important controls on river incision and the pace of landscape development.

Causes of Late Holocene Incision

While dramatic wood clearance resulting from splash damming and logging provides a viable hypothesis for explaining the incision that caused abandonment of straths at a maximum of ca. A.D. 1890, we lack evidence for distinguishing among possible explanations for the onset of strath incision and abandonment at or subsequent to ca. A.D. 830. An upstream-

progressing base-level disturbance is not consistent with the evidence: Strath terrace ages indicate incision in the West Fork Teanaway River was synchronous with that in the main-stem Teanaway (Fig. 13; Table 5), and the upstream propagation would have been implausibly rapid, $\sim 15 \text{ m yr}^{-1}$. Moreover, the speculated drainage capture (Saunders, 1914) would have been initiated much earlier, by deposition of a terminal moraine from the penultimate glaciation. A second possibility, consistent with a systemic, rather than upstream-progressing, cause is that fluvial excavation of the alluvial valley fill from the penultimate glaciation, represented by fill terraces $\sim 35 \text{ m}$ above the current valley bottom (Fig. 1), did not reach the level of the highest strath until the last two millennia; we lack sufficient data on the late Quaternary evolution of the Yakima and Teanaway River valleys to assess this possibility.

An additional possibility is that climatic variability changed the balance of sediment supply and streamflow or caused fires that substantially reduced wood supply to the stream for periods of time. The nearest pollen studies in the Okanogan Highlands to the northeast of the study site indicate a change ca. 2 ka in plant communities suggesting warmer and drier climate (Whitlock, 1992), which could be consistent with a reduction in sediment supply and the onset of incision, but we lack information on whether this change occurred in the east-central Cascade Range or was great enough to trigger strath incision in the Teanaway basin. The Teanaway River may be an example of a system inherently prone to incision, not only because it flows through a mechanically weak and readily weathered lithology (Montgomery, 2004), but because of how basin lithology influences sediment supply; in the West Fork Teanaway, tributaries draining the Roslyn Formation supply little coarse bed material to the river, and what little is contributed breaks down rapidly. The channel's incision into the Roslyn Formation further limits coarse particle recruitment from the flanking alluvium. As a result, bed material is almost entirely made of more competent rock supplied from the distant upper watershed; although rocks in the upper watershed are more competent, they are subject to attrition over the greater distance they travel. Alluvial cover in such settings is likely to be inherently thin and susceptible to fluctuations in the supply and routing of sediment, water, or wood to the channel.

CONCLUSIONS

In the rapidly incising ($\sim 0.01 \text{ m yr}^{-1}$, measured annually) West Fork Teanaway River, the perennially wet, low-flow channel erodes less

rapidly, and by different processes (abrasion) than the seasonally inundated high-flow channel (subaerial weathering that favors plucking, crushing, and macro-abrasion in high-flow events). This observation supports a hypothesis from laboratory experiments that greater rates of weathering of channel margins cause channel margins to erode more rapidly than thalwegs; additionally, measured rates suggest that average annual vertical incision is more rapid in channel margins, pointing to a cross-channel unsteadiness in vertical incision.

This rapid incision in the high-flow channel suggests a mechanism for rapid lateral strath planation: As an incising channel sweeps laterally, removing alluvium from an incipient or low strath surface, it incorporates that surface in the high-flow portion of the channel, where weathering-enhanced vertical incision can rapidly remove the surface, effecting a rapid "top-down" lateral bedrock erosion.

The unsteadiness of vertical bedrock incision recorded by straths in the study area is highlighted by differences among the three strath terrace levels in inferred average incision rates. The fact that inferred average incision rate for the lowest of the three strath terraces, which is currently incising, is greater than that of the older strath terraces suggests that incision rates inferred from straths can be biased by the timing in the cycle of strath terrace formation—the cycle of vertical incision followed by horizontal incision—during which the measurement is made.

Rapid lateral erosion of bedrock banks may provide a mechanism for the transition between periods of vertical incision and periods of lateral incision without requiring any change to external drivers (e.g., change to the supply of water or sediment, or tectonic uplift): Narrowing associated with incision, and resulting higher shear stresses, maintains a condition of low alluvial cover and greater incision rates relative to wider reaches, with narrowing relaxing through time as bedrock terrace risers are laterally planed and the channel widens, decreasing shear stresses, favoring an alluvial cover and limiting further vertical incision.

Anthropogenic removal of fluvial wood from the channel a century ago—and loss of that wood's alluvium-retaining capacity, and thus the alluvium's bed-protecting function—may have caused the most recent episode of strath abandonment and incision. This raises the possibility that the relative abundance of wood and the climatic factors influencing wood size and abundance may be important, unrecognized controls on the pace of channel incision and landscape evolution.

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