TAILINGS FANS AND VALLEY-SPUR CUTOFFS CREATED BY HYDRAULIC MINING

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Received 20 February 2003; Revised 22 November 2003; Accepted 12 January 2004

ABSTRACT

Sand and gravel tailings from nineteenth century open-pit hydraulic gold mines formed large alluvial fans at tributary confluences in the northwestern Sierra Nevada, California. In the Bear River watershed, several of these fans were so large that they blocked main channels for decades. Some channels not only aggraded deeply, but also moved laterally and cut across the inner bends of valley spurs. Now locked in bedrock channels, these valley-spur cutoffs impose local controls on geomorphic, hydraulic, and sedimentary processes. One cutoff has incised 25 m into bedrock over the past century (25 cm a^{-1}) with rapid initial incision rates of up to 50 cm a^{-1} (1884–1890). Recognition of spur cutoffs in the geological record may help to identify large landslides and provide an analogue for a type of natural earthfill dam spillway not prone to catastrophic failures. Tailing fans, valley-spur cutoffs, and the sediment they trap are described from contemporary accounts and recent field conditions in the Bear River watershed. These anthropogenic changes represent a major shift in the watershed from supply-limited to transport-limited sediment budgets and a change in geomorphic processes away from long-term drainage evolution dominated by ingrown meanders. The large volumes of mining sediment stored in these landforms will be slowly released over the next millennium and could be significant to contemporary ecological and public health issues due to recent findings of high mercury loadings associated with hydraulic mines. Copyright © 2004 John Wiley & Sons, Ltd.

KEY WORDS: channel; geomorphology; human impacts; mining sediment; bedrock channels

INTRODUCTION

Hydraulic gold mining in the Sierra Nevada produced large volumes of sediment from 1853 to 1884. Sediment production decreased substantially after 1884 when hydraulic mining was enjoined. More than a billion cubic metres of mine tailings were produced in the Sierra Nevada, particularly in the Yuba, Bear, and American basins (Figure 1). While total mining sediment production was greatest in the Yuba watershed (Gilbert, 1917), sediment yields (volume/area) were greatest in the Bear River basin where the average denudation was approximately 24 cm (8 mm a^{-1}) over an area of 1143 km² (James, 1999). Due to lower channel gradients and stream powers in the mining districts of the Bear River than in the Yuba or American Rivers, a larger proportion of the sediment remains beneath channel beds, in terraces along channel margins, and in fans at tributary confluences. These deposits have begun to receive scrutiny in recent years with the realization that they may contain high levels of mercury and may be relevant to potential dam-removal scenarios for reintroduction of salmon to these rivers. High levels of mercury in fish tissues have been associated with hydraulic-mining sediment in the Bear and Yuba Rivers (May *et al.*, 2000). In addition, high concentrations of elemental mercury were found in tunnels draining the Polar Star and Southern Cross Mines (Hunerlach *et al.*, 1999). Both mines generated tailings fans on the Bear River and were sites of a recent \$1.5 million US Environmental Protection Agency Superfund cleanup site to remove mercury.

Some large tailings fans dammed main channels resulting in lakes and fine-grained deposits upstream. Most tailings fans were breached before the turn of the twentieth century, but much mining sediment remains stored at these locations (Figure 2). Furthermore, tailings fans occasionally caused local channel derangements that locked channels in short, narrow bedrock gorges that now constrain local fluvial adjustments, hydraulics, and

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120° 52' 30"

Figure 1. Hydraulic mining was most extensive in the Yuba, Bear, and North Fork American Rivers. Large mines in the Bear River basin include: CH, Christmas Hill; IH, Independence Hill; LY, Little York; ND, Nichols Diggings; PS, Polar Star and Southern Cross; PU, Pug Ugly and Blue Devil; RD/YB, Red-Dog/You-Bet Complex. This figure is available in colour online at http://www.interscience.wiley.com/journal/espl

sediment transport. At least two of these valley-spur cutoffs now act as local base levels and control large repositories of mining sediment upstream. This paper briefly outlines the genesis and nature of tailings fans and valley-spur cutoffs in the Bear watershed and their geomorphic implications.

Geomorphology and sediment budgets in the study area

The regional geomorphology of the Bear River area has been described elsewhere (James, 1989, 1999). This paper focuses on the nature of the channels, sediment system, and ingrown meanders that generated valley spurs. The parallel drainage pattern of the upper Bear River is similar to many others in the upper Sierra Nevada foothills. Parallel channel patterns are elongated dendritic patterns that result from steep initial conditions free of structural constraints (Howard, 1967). In this region, the drainage formed following Tertiary burial of the pre-existing drainage by deep volcanic lahars, uplift of the Sierra block that generated steep gradients to the southwest, and initiation of consequent streams on the unconsolidated volcanics (Lindgren, 1911). Channels were superposed onto highly deformed Palaeozoic basement rocks.

39°12'30'



Figure 2. Tailings fan and dam at Steephollow Crossing. View down Steephollow Creek (enters from bottom). Tailings came down Wilcox Ravine (from right), pushed creek to left, and dammed main valley. Valley-spur cutoff incised (off photo to left) and fan trenched. Terrace scarp is c. 20 m high. County dirt road on far hill and small utility road down terrace scarp for scale. (Photograph, 1985; adapted from James, 1989; reproduced with permission of Blackwell Publishing)



Figure 3. Ingrown valley meanders on upper Steephollow Creek and Bear River with gentle slopes on spurs on insides of bends and steeper slopes above outer bends. Christmas Hill and Nichols hydraulic mine pits on ridge (see Figure 1). Mining sediment fills Bear River which now has decreased sinuosity. Contours show elevations in metres above mean sea level. (Generalized from US Geological Survey, Dutch Flat Quadrangle, 1:24 000)

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The upper reaches of Steephollow Creek, Greenhorn Creek, and Bear River have ingrown meanders with channel wavelengths and amplitudes equal to the corresponding valley wavelengths and amplitudes (Figure 3). Valley-meander wavelengths along six reaches of the three streams above the mining districts cluster between 270 and 300 m. Within the mining districts valleys were deeply alluviated, and now channels are straighter due to lower meander amplitudes. This straightening results not only from tailings fans pushing channels away from outer valley bends, but also from more freedom of lateral movement in the wide alluvial bottoms and channel steepening in adjustment to elevated sediment loads.

Hillslopes in these mountain watersheds are dominated by colluvium and bedrock. Channels had little prehistoric alluvial storage, so slope weathering and mass-wasting processes controlled pre-mining sediment production. Sediment yields and the distribution of alluvium in such basins depend on the balance between hillslope sediment production and channel transport capacity (Montgomery *et al.*, 1996). Prior to European disturbances, stream powers in the upper reaches of these channels were sufficient to carry most of the sediment supplied to them by hillslope process, so channel-beds were dominated by coarse channel lags, bouldery colluvium, and bedrock. Sediment loads in such mountain streams cannot be estimated from discharge relationships alone, such as through the use of flow-duration and sediment-rating curves, but require estimates of hillslope sediment-delivery processes (Hovius *et al.*, 2000). These conditions can still be seen in the rivers above the mining districts, and they are being re-established in the upper mining districts where historical alluvium is slowly being depleted.

Over a relatively short period of time during hydraulic mining, channels in and below the mines were converted from colluvial-supply systems to alluvial streams with graded profiles and abundant stores of relatively fine alluvium. Sedimentary structures on some high terrace treads indicate that braided channels were common during the peak aggradation phase of the mining period. Through time, the balance between sediment production and transport capacity rapidly shifted from a supply-limited to a transport-limited system, not in response to change in climate or hydrology but to the introduction of massive volumes of fine-grained mining sediment. Subsequently, with decreased sediment production, single-thread alluvial channels formed and most channels in the Bear River mining districts remain in this condition today. Mean annual flows are competent to move most of the coarsest bed material present in the mining districts (James, 1989).

Spatial differences in channel morphology above and below the mines also reflect transitions from supplylimited to transport-limited conditions. Channels above the mining districts are steep, bouldery, and occasionally blocked by large woody debris. Channel forms in these upper reaches are dominantly cascades and step-pools by the mountain stream morphological classification of Montgomery and Buffington (1997), with abundant bedrock exposures. Prior to mining, these forms extended downstream into the mining districts to some point where valleys widen and gradients decrease as channels approach the Bear–Steephollow and Bear–Greenhorn confluences. In the mining districts, channels are presently on deep deposits of relatively fine mining sediment and have pool– riffle and plane-bed morphologies indicative of transport-limited conditions (Montgomery and Buffington, 1997).

TAILINGS FANS

Hydraulic mine tailings were discharged into small tributaries where they filled the steep canyons and formed low-gradient alluvial fans at confluences with main channels. The fans contain large volumes of relatively finegrained sediment and grade to high terraces that often extend more than a kilometre down-valley. Well sorted and rounded gravel textures, graded bedding with no coarsening-upward sequences, and grain-to-grain fabrics in the fan and terrace sediments indicate a fluvial depositional environment. There is no evidence that debris flows or other mass-wasting processes were active in constructing the fans. In some cases, fans dammed the main channels of Steephollow Creek, Greenhorn Creek, and Bear River causing lakes to form and trapping large volumes of mining sediment. With the exception of valley-spur cutoffs described later, the tailings fans have all been breached and severely eroded but still store large volumes of mining sediment (Figure 4). While contemporary descriptions of some tailings fans are relatively detailed, fluvial processes and forms that were associated with them are not known and must be inferred from modern studies of debris fans elsewhere.

Schmidt and Rubin (1995) describe tributary fans in the Green and Colorado River Canyons of Utah and Arizona (USA) and their effects on the local morphology of the main channels. Channel reaches associated with the debris fans are steeper and have coarser bed material than other reaches although fines are deposited below



Figure 4. Remnant of tailings fan coming out of Dutch Flat Canyon (off photo to right) showing terrace tread dipping up Bear River (to left). Fan dammed main channel and held large volumes of mining sediment. (Photograph, 1985). This figure is available in colour online at http://www.interscience.wiley.com/journal/espl

the fans by eddy currents. Four common components of channel complexes occur near the Colorado River debris fans: (1) a backwater upstream, (2) channel constriction at the fan, (3) one or more eddies and associated bars downstream, and (4) a gravel bar downstream (Schmidt and Rubin, 1995). The morphology of these fan–eddy complexes may differ from the relatively fine-grained fans that formed in the Sierra Nevada due to a different valley morphology. Rapid incision into the Colorado Plateau generated entrenched meanders in deep symmetrical, steep-walled canyons with no valley spurs. This is in contrast to the ingrown meanders of the Sierra Nevada valleys where spurs are common opposite tributary junctions. In a general sense, however, the Sierra Nevada tailings fans may have resembled fan–eddy complexes. They clearly had backwaters upstream with channel constrictions at the fan toe. They may also have had eddies and gravel bars downstream, although these deposits have been removed by erosion.

Contemporary descriptions of tailings fans

Descriptions of tailings fans that formed dams at several locations in the Bear River are available from contemporary court testimony and government surveys concerned with mining sediment (Table I). For example, a hydraulic miner and local resident testified about three large tailings-fan dams on Bear River near Dutch Flat:

Three... The outlet of the Yankee, the outlet of the Southern Cross, and the outlet of the Polar Star. There may be others above, but I never went down... They restrain all of the heavy tailings above... [They're composed of] Gravel and boulders washed out of the claims... Heavy material, varying from sand to stones 30 inches [76 cm] in diameter ... They are to all appearances permanent ... At the mouth of Dutch Flat Canyon there has been a dam since 1872. Above the dam has been filled with what you gentlemen please to call *slickens*, or slum that has not been washed out there since 1872... It is immediately above the outlet of the Yankee.

T. B. Ludlum, in Keyes (1878)

The dam at the mouth of Dutch Flat Canyon was breached long ago (Figure 4). It has open-work gravel and sand with upper beds and terrace treads dipping up the main Bear valley.

The depth of mining sediment remaining beneath the fans is not known because channels have not returned to pre-mining base levels and subsurface data are lacking. Minimum values can be estimated from two topographic surveys in 1870 and 1879 using an aneroid barometer. Comparison of the two surveys indicates 30 and

Table 1	I. 1	Large	tailings	fans	in	Bear	River

Bear River				
Little Bear River	Nary Red and Polar Star mines			
below Little Bear R.	Polar Star Mine; est. c. 1874; failed in 1883 exposing c. 1.3 m lake seds; Southern Cross Mine; fan c. 90 m below Polar Star fan			
Dutch Flat Canyon	Yankee and Thompson Hill Mines; Stable 1872 to 1878 (Figure 4)			
Squires Ravine	Pug Ugly and Blue Devil Mines			
Steephollow Creek				
Wilcox Ravine	You-Bet Mines; Est. 1860–62; caused spur cutoff (Figure 2)			
Hawkins (Birdseye) Cn.	Walloupa, Neece and West, and You-Bet Mines			
Greenhorn Creek				
Prior Ravine	Quaker Hill Mines			
Gas Canyon	Hunts Hill Mines			
South Greenhorn	Buckeye, Boston Hill, and Bunker Hill Mines			
unnamed tributary	Poore Mine			
Above Red Dog Ford	Tunnel from Independence Hill Mine; caused spur cutoff (Figure 11)			
Arkansas Canyon	Red Dog Mines; since 1860			
Missouri Canyon	Red-Dog Mines			

From testimony in Keyes (1878), surveys by Pettee (Whitney, 1880) and Turner (1891) (cf. James, 1988), and field evidence. Not a complete list; does not include many smaller tailings fans.

41 m of aggradation in that nine-year interval on the Dutch Flat Canyon fan near Little York Crossing and the Wilcox Ravine fan at Steephollow Crossing, respectively (Whitney, 1880). Professor W. H. Pettee estimated in 1871 that there had already been 15 to 23 m of mining sediment at these sites prior to the initial survey (Whitney, 1880). Thus, fan depths in 1879 were approximately 50 and 60 m at the Dutch Flat Canyon and Steephollow Crossing fans, respectively.

Based on field observations in 1889 and 1890, Turner (1891) described tailings-fan dams at several locations. At the fan below the Polar Star Mine near Dutch Flat, he estimated the depth of mining sediment to be 46 m and plotted it as a high reach on a longitudinal profile. By the time of Turner's survey, the fans and high terraces were being incised. On Steephollow Creek above Wilcox Ravine, Turner (1891) described terraces 2 or 3 m above the channel bed and further upstream below the Christmas Hill Mine terraces were about 6 m above the bed.

The Wilcox Ravine fan at Steephollow Crossing is a notable tailings fan built of sediment from the You-Bet mine complex (Figure 5). Above Steephollow Crossing a deposit of laminated clays and other lacustrine sediment – an anomaly in these mountain rivers – corroborates the documentary record of a lake and fine sediment trapped behind this fan. The tailings fan at Wilcox Ravine began to form in the early 1860s and persisted intact until at least 1890 when Turner described incipient channel incision. A topographic survey in 1989 with transit, rod, and fibreglass tape indicates that the channel had incised c. 30 m below the fan surface downstream of Steephollow Crossing (Figure 6). An unknown depth of sediment remains beneath this fan (cf. Figure 2). The Steephollow fan is a prime example of a valley-spur cutoff that shifted the channel out of its former location and now regulates incision.

VALLEY-SPUR CUTOFFS

In the most general sense, spurs are small ridges protruding from the sides of valleys. Spurs include ridges on the inside bends of meanders, and cutoff spurs include the classic mode of meander-loop cutoffs in which a stream cuts across a narrow meander neck thus abandoning a meander loop. With deeply incised meanders where lateral migration has dominated over down-valley meander translation, however, bedrock spurs slope steeply down to meander bends and there are no low, narrow meander necks. Spurs in the Sierra foothills fit this description (Figure 3), and meander cutoffs by the action of the river alone are rare.

The valley-spur cutoffs described here are landforms created when a tributary fan dammed the main channel causing it to rise up against a bend on the far valley wall (Figures 7 and 8). The stream cut across the bedrock



Figure 5. Bear River mining districts. (A) Mining sediment in channels (sinuous white bands) between hydraulic mines on uplands (white patches). Red-Dog/You-Bet mine complex tailed into Steephollow Creek from north side. (B) Close-up of Wilcox Ravine fan at Steephollow Crossing. Axis of valley spur along arrow labelled 'spur'; cutoff crosses narrow bands of trees near tip of arrow. (NAPP aerial photograph flown in 1987)



Figure 6. Valley cross-section c. 100 m below Steephollow Crossing showing c. 30 m of incision into fan. Breaks in slope on right side are terraces. (Surveyed 1989)



Figure 7. Schematic of valley-spur cutoff at Steephollow Crossing (view downstream). (1) Pre-dam section. (2) Episodic sedimentation from tributary dams main valley forcing channel up against far valley wall. (3) Channel incises across high spur

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1
Contemporary
Alluvium
Terrace
Colluvium
& Bedrock

2
Tunnel
from Mine
& Tailings
Fan

3
Channel
incised into
fan and spur

Figure 8. Sketch map of spur cutoff on Greenhorn Creek. (1) Pre-mining valley meandered to east around spur. (2) Mine delivered tailings that built fan and forced channel up onto spur. (3) Channel incised into spur where it remains. This figure is available in colour online at http://www.interscience.wiley.com/journal/espl



Figure 9. Schematic long-profile through tailings dam. (1) Lake forms behind dam and fills with mining sediment. (2) If valley-spur cutoff forms it controls long-profile and sediment release. This figure is available in colour online at http://www.interscience.wiley.com/journal/espl

spur at a high level, incised a steep-walled notch, and got locked in this new position as the channel degraded. Cutoff spurs control long-profile readjustments as well as the release of sediment stored in and behind the fan that created them (Figure 9). These cutoffs differ from common channel derangements in unconsolidated materials because their bedrock margin prevents lateral channel migration and retards vertical incision. Lateral channel displacements in response to landslides or other natural dams are common, but unless the spillway is in bedrock, competent floods may rework the unconsolidated dam material and re-excavate the valley bottom. Spur cutoffs behave like bedrock channels in which the entire channel margin is a bedrock notch or gorge, although bedrock is limited in the longitudinal dimension to a relatively short reach. Valley-spur cutoffs represent a change in channel planform, sinuosity, and valley-bottom morphology including a sudden narrowing at the constriction. They certainly have occurred elsewhere in mountain streams in response to natural dams, although specific references to them in the literature have been elusive.

Valley-spur cutoffs are known at two sites in the Bear River basin: on Steephollow Creek below Wilcox Ravine (Steephollow Crossing) and on Greenhorn Creek above Red Dog Ford (Figure 1). The drainage areas of these cutoffs are 55 km² at Steephollow Crossing and 47 km² above Red Dog Ford. Similar basin areas may suggest



Figure 10. View up Steephollow Creek through valley-spur cutoff at Steephollow Crossing. Spur sloping right to left; fan from distant left beyond notch. Vertical incision through argillite was 24-9 meters from 1884 to 1985. This figure is available in colour online at http://www.interscience.wiley.com/journal/espl

an optimal relationship between tailings produced, valley size, and stream powers that could incise the fans during construction. Conversely, drainage area may simply represent the position of these sites in the central mining districts where large mines were operating, channel gradients were decreasing, and aggradation was pervasive.

The most notable of the valley-spur cutoffs is located at Steephollow Crossing (Figure 10). Turner (1891) recognized not only the process in its early stages, but also the role it was to play in regulating releases of mining sediment:

The great mass of gravel coming down Wilcox Ravine choked up the bed of Steep Hollow and forced the stream to the left bank and finally across a point or ridge opposite; and through the slate rock the gravel-bearing water has cut a channel, which it is rapidly deepening by cutting back as a fall, the height of which is now 10 feet [3 m]. This tends to moderate the rate of the erosion of the gravel above, and will act more and more effectively until it has lowered its waste weir level. F. C. Turner (1891, p. 3062)

The Steephollow spur cutoff was blocked with a 14.6 m high concrete dam in 1924 to allow licenced hydraulic mining of 29 000 m³ of sediment stored behind it. A tunnel through the bedrock spur apparently acted as a spillway for the dam which failed in 1925 (California Debris Commission archives, US Army Corps of Engineers). The dam crest was presumably below the top of the bedrock spur at the level of the spillway tunnel.

Rates of bedrock incision

Bedrock channels are generally slow to erode. The valley-spur cutoffs, however, have incised relatively rapidly due to their limited bedrock extent, weak rock, and high flow powers with abundant abrasion tools. The 3 m waterfall observed by Turner at Steephollow Crossing in 1891 is interpreted as incision into weathered regolith that does not include mining sediment. Although he describes a rapidly deepening headcut that apparently had not yet breached the length of the spur, a 3 m depth of incision in 1890 is used to calculate incision rates. If bedrock incision is assumed to have begun with the injunction of 1884, the initial incision rate was 50 cm a^{-1} for the first six years. The height of the concrete dam in 1924 provides a minimum depth of incision by that

Source	Number	$Mean^* (cm a^{-1})$	Maximum (cm a ⁻¹)
Long-term examples Pazzaglia <i>et al.</i> (1998, table 1)	15	0.052	2
Short-term examples [†] Tinkler and Wohl (1998, table 2)	5	6.78	38‡

Table II. Bedrock channel-incision rates

* Where ranges were reported, mean was calculated using midpoint of range.

† Mostly sedimentary rocks over periods from 1 to 300 years.

‡ Observed in Virginia over 2-year period.

time, since the top of the dam would not have been higher than the bedrock and was probably at the tunnel spillway approximately 5 m lower. Based on a dam 14.6 m high, the notch had deepened at least another 11.6 m in the 34 years from 1890 to 1924, at a rate of at least 34 cm a^{-1} . The notch was 24.9 m deep in 1985 when measured with a weighted fibreglass tape from the top of the bridge floor that was approximately level with the low point of the bedrock surface at the notch. The bridge floor was 2 or 3 m below the projected fan surface, but this depth is not included in bedrock incision-rate calculations to account for the channel depth at the time of initial incision. The 25 m of total incision into bedrock represents a long-term average incision rate of 25 cm a^{-1} from 1884 to 1985. The bridge collapsed shortly after 1985, so subsequent measurements have not been made.

Incision rates were initially rapid and decreased through time. Average rates were up to 50 cm a^{-1} from 1884 to 1890, at least 34 cm a^{-1} from 1890 to 1924, and no more than 17 cm a^{-1} from 1925 to 1985. Given that the 1924 depth of incision is a minimum value, it is possible that most of the 25 m of incision had been completed by that time. Early incision was rapid as the knickpoint observed by Turner worked headward through the weathered regolith and established a channel notch that increased flood depths. Incision rates reached a maximum when the notch was deep enough to accommodate maximum flood depths, and presumably decreased later as channel gradients and sediment loads decreased. Maximum incision rates in bedrock channels are not necessarily associated with maximum sediment transport rates due to potential protection of the bed by alluvium (Pazzaglia *et al.*, 1998). In the hydraulic environment of the Steephollow spur gorge, however, accumulations of sediment were probably negligible and decreased rates of sediment transport probably resulted in decreased abrasion. Maintenance of the narrow gorge shape suggests a dominance of vertical incision and lack of sedimentation in the gorge. In contrast, the cutoff spur in Greenhorn Creek was floored by alluvium throughout the 1980s although bedrock was recently exposed due to degradation downstream.

As might be expected, bedrock channel-incision rates from 17 to 50 cm a^{-1} are very rapid in comparison to rates recorded for bedrock channels at the reach or basin scale. Incision rates over Quaternary or longer time scales are typically two to three orders of magnitude slower and range up to a maximum of only 2 cm a^{-1} (Table II). Rapid incision rates over time periods more comparable to this study are on the order of 2 to 10 cm a^{-1} in sedimentary rocks, although rates have been recorded up to 38 cm a^{-1} . The bedrock at both of the Bear basin spurs is argillite of the Calaveras Complex (Saucedo and Wagner, 1992) with nearly vertical folia that strike approximately parallel to the notch cut by the channels. Thus, channel erosion exploited structural weaknesses in the rock that encouraged incision into a narrow, vertical cut. Furthermore, large supplies of mining sediment provided a steady supply of abrasion tools.

Geomorphic and hydraulic processes

Fluvial processes are severely constrained where channels are locked in a bedrock notch. Many standard approaches for estimating flows, sediment transport, or erosion are not valid in this environment due to the strongly non-uniform flows through the spur cutoffs. For example, calculations based on the Manning equation should not be applied at these locations. Bedrock channels do not exhibit hydraulic geometry relationships, and their longitudinal profiles do not conform to graded conditions because morphologic and vertical adjustments no longer reflect moderate-magnitude events (Pazzaglia *et al.*, 1998).



Figure 11. View up Greenhorn Creek through valley-spur cutoff above Red Dog Ford. Metamorphic exposure in bed and sides. Spur slopes from left; fan from right. Depth of notch is *c*. 12 m; width narrows to *c*. 10 per cent of valley width above and below. (Photograph September 2001). This figure is available in colour online at http://www.interscience.wiley.com/journal/espl

Channel constrictions may enhance sediment transport through the local reach due to steeper and deeper flows, but they inhibit sediment deliveries from upstream. Gradients through cutoff spurs are locally steepened for three reasons. First, channel aggradation during deposition of the dam initially steepens the profile. Second, alluvium may be removed below the cutoff while bedrock resists erosion and imposes a local base level upstream. Finally, the cutoff decreases channel sinuosity because the channel no longer circumvents the spur. While steepening encourages erosion and transport of available sediment through the reach, channel confinement in a bedrock gorge prevents lateral migration and valley-bottom widening and inhibits removal of sediment stored locally. Retarded but protracted delivery of loose valley-bottom sediment may persist over long periods of time even after longitudinal adjustments are complete.

Knickpoint retreat may have operated locally but is not the dominant on-going process in the Bear River spur cutoffs. There are no falls or downstream pools in the Greenhorn cutoff (Figure 11), yet the bed of the notch has lowered perceptibly since 1985. The constrictions act as a local base level and limit sediment transport by preventing bed scour and decreasing the energy gradient above the notch during major floods. Early establishment of the Steephollow cutoff was by erosion of the fan toe below the spur which created a waterfall (Turner, 1891). Retreat of this local knickpoint through the spur was followed by rapid up-valley migration once past the bedrock of the longitudinally limited spur. The bed of Steephollow Creek now drops approximately 5 m through the gorge (Curtis, 1999) ending in a shallow pool on the downstream side. This break in slope reflects the local hydraulics and does not necessarily indicate that the dominant erosion process is upstream migration of bedrock ledges. Under extreme hydraulic conditions of supercritical flows with abundant supplies of sand and gravel as tools for abrasion, erosion is intense and rock-sculpting processes can lower as well as wear back the bed (Hancock *et al.*, 1998).

Implications of spur cutoffs

Although spur cutoffs have not been identified elsewhere in the region, the process has not been widely recognized and the landform may have gone unnoticed. Spur cutoffs did not form on main channels of the Feather, Yuba, or American Rivers. These valleys have ingrown meanders with abundant spurs, but high stream powers prevented large tailings fans from developing. Cutoff spurs may be present on upper tributaries such as Shady or Spring Creeks, however, and if so, should be mapped as loci controlling the long-term release of mining sediment.

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Valley-spur cutoffs can result from natural events that dam river valleys such as landslides, vulcanism, and glaciers. Of the six types of landslide dams identified by Costa and Schuster (1988) the two most frequently occurring types (Types II and III) extend across the entire valley floor and could produce cutoff spurs in canyons with the appropriate morphology. Spur cutoffs require rapid construction of an obstruction large enough to force the main channel up from the valley bottom onto bedrock on the far valley side. Identification of valley-spur cutoffs in the geologic record, therefore, could aid in recognition of past major landslide events and provide indications of landslide susceptibility for hazard assessments.

Spur cutoffs can result in a slow, controlled dam breach by gradual lowering of a natural spillway. This process may be desirable given the catastrophic nature of dam-outburst floods generated by sudden failure of unconsolidated materials. Due to the lack of a protected spillway or outlet, most natural-dam failures are caused by overtopping followed by rapid breaching (Costa and Schuster, 1988). Furthermore, most failures occur rapidly; approximately 50 per cent occur within 10 days and 85 per cent within the first year of dam establishment. Thus, recognition that a bedrock spillway has developed is relevant to forecasting and dam-breach modelling. If natural dam conditions are right, it may be possible in early stages of fluvial adjustment to train the channel against the far valley wall and initiate a spur cutoff. These strategies should take into account, however, the tendency for channels to initially incise along inner-bend cutoffs but then to aggrade there and shift toward the outside bend (Shepherd and Schumm, 1974).

One example of a natural dam with a bedrock spillway has been well documented. The Slumgullion earthflow dammed Lake Fork of the Gunnison River in southwestern Colorado about 700 years ago and a stable spillway developed in bedrock (Costa and Schuster, 1988; Schuster, 1996). The channel shifted about 200 m away from the earthflow source against the far valley wall of volcanic bedrock and colluvium and ended up 28 m higher than its original elevation with a 25 m waterfall (Schuster, 1996). It is not clear if this example involves a spur cutoff because the subsurface topography of the former valley bottom is not known, but it illustrates the benefit of a natural bedrock spillway.

Evolution of valley morphology, meanders, and spurs

Valley spurs are ubiquitous in mountain valleys because they result from the most common form of incised valley meanders; that is, meanders cut into bedrock. Two types of incised meanders are commonly distinguished (Rich, 1914; Jackson, 1997). *Ingrown meanders* created by the combination of lateral migration and vertical incision have asymmetrical valleys with steeply cut outer bends and sloping inside bends (valley spurs) on alternate sides of the valley. Ingrown meanders represent incision that is slow enough that lateral valley migration is substantial and are associated with increasing meander-wave amplitudes and valley sinuosities. In contrast, *entrenched meanders* created by vertical incision alone have symmetrical valley cross-sections at bends with fixed meander geometries. Entrenched meanders are not as common and represent incision that is too rapid for lateral migration to keep pace.

The interpretation of incised meanders is encumbered by a long history of genetic assumptions that are no longer considered universal. A long-held theory that incised meanders are inherited from meanders developed on alluvial floodplains and superposed onto structures below was advocated by Davis (1896). Dury (1964) explained large incised meanders as a result of former large discharges, implying substantial palaeohydrologic changes. He cited long valley wavelengths and asymmetric bedrock valley-bottom cross-sections as evidence. These interpretations were called into question in the 1970s. Valley meanders can be generated by on-going processes and are not necessarily inherited (Shepherd and Schumm, 1974). Palmquist (1975) proposed that asymmetric cross-sections can result from the preferred position of channels in valleys and demonstrated that channels tend to occupy the outside of valley bends. He postulated that bed scour during large floods results in maximum bedrock depths at outer bends corresponding with the maximum frequency of channel positions. An even simpler hypothesis is that extreme floods tend to concentrate erosion at valley bends regardless of where the channel was initially. Two-dimensional flow models simulating extreme flood conditions have shown that perturbations in the flow at bends cause local shear-stress maxima that rival shear stresses at narrow canyon constrictions (Miller, 1995). By either hypothesis, the asymmetric cross-section form in mountain valleys may simply represent the location of maximum scour depth during extreme floods and requires neither inheritance nor a palaeoclimate interpretation.

Ingrown meanders and spur lengths may reflect long-term tributary sediment delivery rates. Scheidegger (1991, p. 231) postulated that in initial stages of mountain valley erosion, cross-currents are generated at tributary confluences that enhance erosion and can initiate bends. Incipient bends further concentrate erosion on outer bends perpetuating meander creation. Where valley meanders exploit tributary confluences, it follows that lateral erosion at tributaries will dominate only where tributary sediment loads are not high enough to build and maintain debris fans that protect the outer bend. Conversely, if tributary loads are high enough to build fans and force channels away from the confluence, the main channel will be encouraged to straighten. In this way, ingrown meander morphology reflects long-term interactions between sediment production in tributaries and main channel sediment transport capacity. Transport is determined by local hydraulics, and in bedrock valleys where vertical adjustments are constrained, channel gradients are largely controlled by sinuosity adjustments. During climatic or tectonic periods of low main-channel flow energies or high sediment production in tributaries, sediment accumulates in tributary fans, the main channel straightens and steepens, and flow energy increases until the transport capacity matches the sediment supply and tributary fans at tributary junctions are eroded, sinuosity increases, and flow energy or low tributary sediment production, fans at tributary junctions are eroded, sinuosity increases, and flow energy decreases.

Many valleys throughout the upper Sierra Nevada foothills are sinuous with ingrown meanders that result in valley spurs sloping down to the valley bottom on the insides of bends (Figure 3). Channels were superpositioned through Cenozoic volcanics and ingrown meanders developed as channels cut through the unconsolidated volcanic overburden and encountered the hard underlying basement rocks. Steeply sloping spurs on inner bends of both sides of the valley indicate progressive increases in meander amplitudes, valley sinuosities, and spur lengths. Most small tributaries enter channels on the outsides of bends, suggesting that valley meanders tended to grow into tributary confluences.

Prehistoric debris fans are not common in valley bottoms of the study area suggesting ample stream energy to maintain meander-wave amplitudes in unaltered valleys. The parallel drainage network of these streams results in narrow interfluves, small tributary contributing areas, and low tributary sediment loads under natural conditions. Ingrown meanders in this environment were slowly growing in amplitude until the rapid introduction of mining sediment arrested meander incision in the mining districts and replaced it with a sediment budget dominated by alluvial storage in main channels and many tributaries. Mining reversed the long-term valley incision process by aggrading channels, building large tailings fans at tributary junctions, decreasing sinuosities, and cutting through valley spurs in at least two locations.

CONCLUSIONS

Tailings fans are geomorphic vestiges of the gold-mining era that determined the sedimentology and loci of maximum aggradation during the peak period of hydraulic mining. They now represent large mining-sediment repositories. Where the fans are controlled by valley-spur cutoffs, their spillways act as local base-level controls regulating longitudinal profile adjustments. Vertical incision rates at the Steephollow cutoff began rapidly at rates approaching 50 cm a^{-1} between 1884 and 1890, but slowed to no more than 17 cm a^{-1} from 1925 to 1985. Yet, vertical readjustments are far from complete. At both sites, an unknown depth of mining sediment remains below the present channel bed upstream and downstream of the spur cutoff. Furthermore, vertical readjustments of the channels were rapid relative to horizontal readjustments. Horizontal channel movements at the spur cutoffs are severely constrained, so fan deposits at these sites are not easily attacked by lateral planation. Thus, a considerable volume of mining sediment remains at these locations and is being slowly eroded by gullies and other hillslope processes. Long after vertical adjustments are complete, mining sediment from these sites will continue to be remobilized at a relatively slow rate.

Tailings fans and valley-spur cutoffs represent a reversal of long-term geomorphic processes in the Bear Basin. Channels were formerly supply-limited with step-pool or cascade morphologies and relatively high sinuosities. The rapid introduction of mining sediment altered rivers within and below the mining districts. They now are transport-limited systems with alluvial valley floors and channels characterized by pool-riffle and plane-bed morphologies and decreased sinuosities. Sediment storage behind valley-spur cutoffs represents a substantial geomorphic impact of human activities that will persist long after those activities were halted.

L. A. JAMES

ACKNOWLEDGEMENTS

George Dury opened my eyes to the importance of river and valley meanders when I was a budding young geomorphologist. I may see them differently than he did, but I certainly see them more clearly after his guidance. Daniel Sarlitto and Robert Wilson assisted with field work. Research benefited from funding through the National Science Foundation, Grant SES 8822436.

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