Geomorphic control of persistent mine impacts in a Yellowstone Park stream and implications for the recovery of fluvial systems

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ABSTRACT

A half-century after mine closure, metal contamination from sulfide ore mining in the headwaters continues to impair riparian vegetation and aquatic macroinvertebrates along Soda Butte Creek, Yellowstone National Park. A tailings dam failure in 1950 emplaced metal-rich sediment at high flood-plain levels, above 50 yr to 100 yr flood stages in 1996 and 1997. These large natural floods removed only a small part of the contaminated sediment through bank erosion; they also failed to lower in-channel Cu concentrations, because increased erosion of mine waste during high flows balances increased inputs of uncontaminated sediments, generating no net change in concentrations. Geomorphic processes controlling movement of contaminated sediments indicate that mine impacts will persist for centuries in Soda Butte Creek and imply long-lasting impacts in similarly affected streams worldwide.

Keywords: fluvial, flood plains, mining, sediments, Yellowstone Park, contaminants, pollution.

INTRODUCTION

Heavy metal loading of streams from metal mining has been extensively documented (see review by Salomons, 1995). In many basins, however, multiple metal sources and poor historic data on aquatic and riparian biota hinder our ability to isolate mining impacts at watershed scales and understand processes controlling contaminant distribution and persistence after mine closure.

Soda Butte Creek provides a natural laboratory that minimizes these complications. Headwaters in Montana drain the New World mining district before entering relatively pristine Yellowstone National Park (Fig. 1). Mining and ore processing was conducted from 1870 to 1953 in pyritic Au-Cu-As replacement and skarn deposits and minor Pb-Ag-Zn veins, all associated with zoned porphyry alteration produced by Eocene intrusions (Elliot et al., 1992; Johnson and Meinert, 1994). Mine workings include open-pit and underground excavations, mill sites, waste-rock piles, tailings, slag, and roads. Gold occurs pri-

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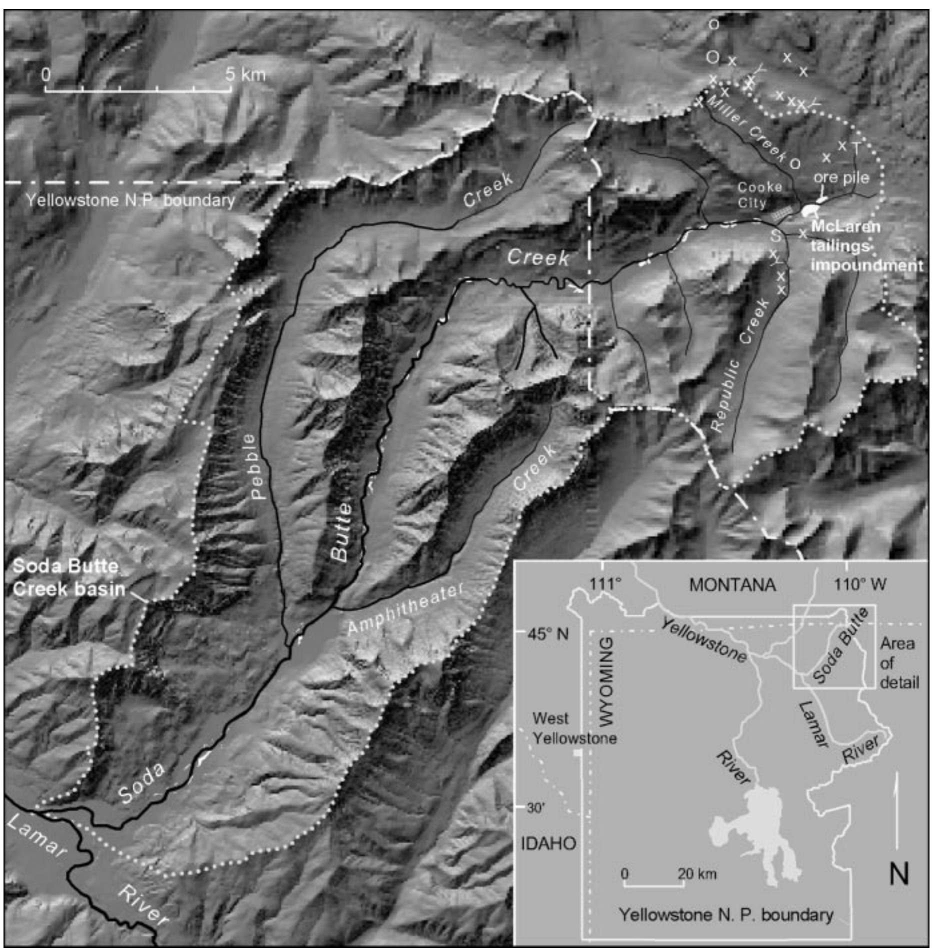

Figure 1. Map of Soda Butte Creek, Montana and Wyoming, showing mine workings (white symbols) in New World district: X—small mine or prospect; Y—adit; O—open-pit mine; T—small tailings pond; S—small smelter site with slag. Mine workings south of Cooke City are small sites in Pb-Ag-Zn veins; others are associated with Cu-Au-Ag deposits. White patches along Soda Butte Creek below McLaren tailings impoundment indicate mapped flood-plain tailings deposits from 1950 dam failure. N.P.—National Park. Mine impacts derive primarily from Miller Creek drainage and tailings impoundment.

TABLE 1. METAL CONCENTRATIONS IN MINE WASTE AND SODA BUTTE CREEK FLOOD-PLAIN DEPOSITS

	As (mg/kg)	Cu (mg/kg)	Fe (%)	Pb (mg/kg)	Zn (mg/kg)
McLaren impoundment tailings*					
Mean	—	3131	25.3	1389	527
Std. Dev.	—	714	1.85	377	348
Range	—	1810-4270	22.8-27.9	750-2000	250-1000
Flood-plain tailings deposits†					
Mean	57	364	7.2	156	137
Std. Dev.	53	224	2.6	152	87
Range	6-271	96-1220	3.5-16.0	39-736	70-649
Premium overbank sediments†,§					
Mean	1.1	27	3.5	10	55
Std. Dev.	0.4	6.3	1.0	2.1	8.5
Range	n.d.-2.0	18-37	2.8-5.0	8-13	45-69
Postmining overbank sediments†,**					
Mean	1.6	42	3.7	18	66
Std. Dev.	1.8	14.1	1.6	5.5	14.6
Range	n.d.-6.0	26-68	2.7-6.4	10-24	50-87

Note: All values are depth-weighted averages for entire stratigraphic thickness of tailings or deposits at a site. Std. Dev. is standard deviation. n.d.: Below detection limit.

*Data are based on samples from nine drill holes through the full depth of the tailings (Sonderegger et al., 1975).

†Analyses by aqua-regia extraction and inductively coupled plasma-atomic emission spectroscopy. Flood-plain tailings values are from 50 deposits and are based on 179 analyses (1-6 samples per deposit).

§Sampled at seven localities on dated late Holocene fluvial terraces of middle to lower Soda Butte Creek (Meyer et al., 1995). Textures are similar to postmining overbank deposits.

**Samples of two 1991, three 1996, and three undated modern overbank deposits where 1950 tailings dam-break deposits are not present, from localities along middle to lower Soda Butte Creek.

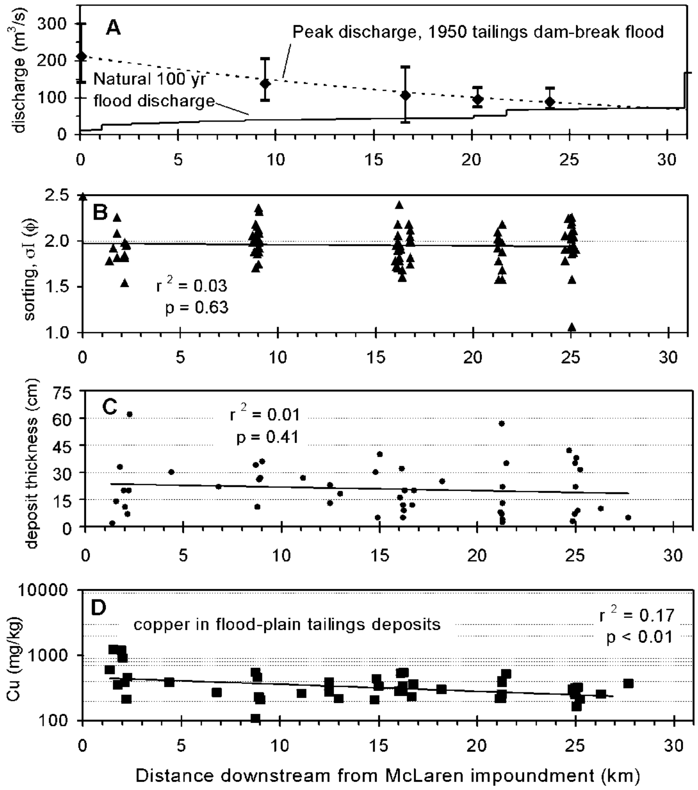

Figure 2. Characteristics of flood flows and tailings deposits in Soda Butte Creek. A: Peak discharge during 1950 tailings impoundment failure compared to 100 yr flood discharge; error bars show range of uncertainty. Tailings were emplaced with no discernible change in particle size, sorting (B), or deposit thickness (C) downstream, indicating little effective downstream depletion of sediment and dominant control of flood-plain morphology on deposit thickness. D: Despite downstream decrease by dilution, Cu concentrations are approximately five times background levels 25 km below tailings. All r^2 values in this figure are adjusted for sample size.

marily within pyrite and chalcopyrite, so mine wastes are acidic and Cu rich. Our stream sediment data and work by Elliot et al. (1992) show that Cu and Pb enrichment is confined to the New World district. Bedrock downstream of the district is dominated by unaltered Eocene andesitic volcaniclastics with low Cu concentrations (mean ~18 mg/kg; Elliot et al., 1983) and Paleozoic carbonates and shales with similarly low Cu content. High relief and steep slopes on erodible rocks give rise to dynamic hillslope and fluvial systems in this basin (Meyer et al., 1995), so active transport of sediment-bound metals is expected. Here we examine geomorphic processes controlling Cu concentrations in channel and flood-plain sediments along Soda Butte Creek, document associated biotic impacts, and discuss implications for the persistence of mine impacts in stream systems.

IMPOUNDMENT FAILURE AND FLOOD-PLAIN CONTAMINATION

The mill site and tailings impoundment for the McLaren gold mine were operated directly on Soda Butte Creek from 1933 to 1953 and had particular impact on the stream (Fig. 1). The impoundment currently holds 1.3×10^5 m^3 of tailings that contain >20% pyrite by volume and are enriched in Cu, Pb, and lesser As and Zn (Table 1) (Sonderegger et al., 1975). The earthen impoundment dam failed in June 1950, releasing ~4.1×10^4 m^3 of water and an unknown mass of tailings. We reconstructed peak discharge using a dam-break model (Costa, 1988) at the impoundment and the slope-area method (Benson and Dalrymple, 1967) at four stable reaches where tailings deposits mark peak stage. In upper Soda Butte Creek, peak discharge was an order of magnitude greater than the 100 yr flood (Q_{100}; Omang et al., 1986), declining by attenuation to ~Q_{100} ~30 km downstream (Fig. 2A). In accordance with discharge reconstructions, peak stage at 25 km in the dam-break flood was a few decimeters higher than in 1996, when gaged discharge approximated Q_{100} (Epstein and Meyer, 1997).

Limited water volume in the 1950 dam break produced a flood lasting <1 h. Comparison of 1949 and 1954 aerial photographs shows little flood-plain and channel erosion, probably because stream power exceeded erosion thresholds only briefly (e.g., Costa and O'Connor, 1995). Tailings accumulated on flood plains along the entire valley, however, in patchy deposits of sandy silt similar in texture to normal overbank deposits (Ewing, 1997) (Fig. 1). These deposits range from thin sheets to abandoned channel fills as much as 0.7 m thick. They are readily distinguished from typical overbank sediments by strong oxidation, abundant sand-sized pyrite grains, and consistent position at or near the surface of the active flood plain.

Using detailed mapping and Pb concentrations, we estimate that the flood-plain deposits contain tailings equivalent to 2%–3% of the mass of tailings currently in the impoundment. Mean Cu and Pb concentrations in flood-plain tailings deposits are about one order of magnitude less than in the impoundment, but one order of magnitude greater than in premining Holocene overbank deposits (Meyer et al., 1995; Carolan, 1997) (Table 1). The pH of tailings deposits is typically <6.5 and as low as 3.4 (Carolan, 1997; Stoughton and Marcus, 2000). We found no significant downstream trends in particle size, sorting (Fig. 2B), or deposit thickness (Fig. 2C), consistent with rapid deposition during a brief sediment-charged flood. Metal concentrations are highly variable between sites and within stratigraphic sections, but decrease exponentially downstream (Fig. 2D), probably from dilution by uncontaminated sediment entrained in the flood. Nonetheless, Cu concentrations in some layers exceed 1000 mg/kg as far as 16 km below the impoundment (Carolan, 1997; Stoughton and Marcus, 2000).

Exposed tailings deposits create patches barren of vegetation to 25 km below the impoundment, well within Yellowstone National Park. No such barren patches exist on premining fluvial terraces. In

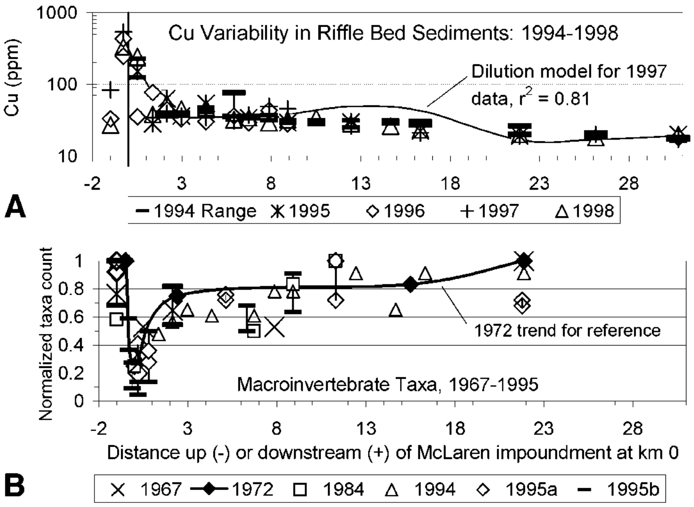

Figure 3. Copper in active channel bed sediments and its impacts on aquatic insects in Soda Butte Creek. A: Despite major floods, there has been little change in bed sediment Cu since 1994. Sampling procedures were described by Ladd et al. (1998). r^2 value is adjusted for sample size. B: Taxa counts since 1967 along Soda Butte Creek display same pattern. Taxa numbers have not demonstrated consistent improvements at any one site, consistent with unchanging Cu concentrations over time. Taxa counts are normalized to maximum value of 1.0 for each date to remove variability from different sampling techniques. 1967 data are from Bureau of Sport Fisheries and Wildlife (1974), 1972 data are from Chadwick (1974), and 1984 data are from Mangum (1986). Marcus (1995a in B) and Nimmo (1995b in B) independently collected samples in 1995.

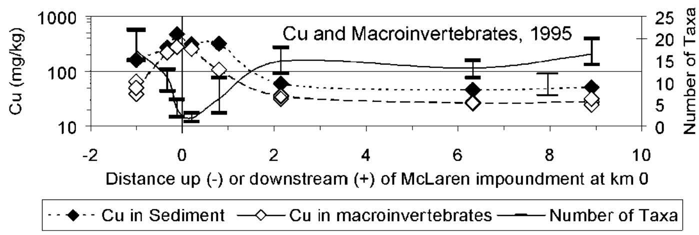

Figure 4. Relations between Cu in sediments and macroinvertebrates. Copper concentrations in bed sediments are correlated to Cu concentrations in macroinvertebrate tissues (r^2 = 0.80, value adjusted for sample size) and inversely correlated (r^2 = 0.48) to number of taxa at sites along Soda Butte Creek.

four study areas 11–23 km downstream of the impoundment, metals have significantly depressed the diversity, density, and biomass of grasses (Stoughton and Marcus, 2000). The diversity of grasses drops sharply at Cu concentrations above 315 mg/kg. Similar threshold relations occur for As at 22 mg/kg, Fe at 4.2%, Pb at 65 mg/kg, and Zn at 170 mg/kg, concentrations found only where tailings deposits are present (Table 1). Lodgepole pines (*Pinus contorta*) tolerate acid soils and have colonized some otherwise barren tailings deposits.

CONTAMINATION OF ACTIVE CHANNEL SEDIMENTS

In the active channel, biotic impacts of metals are probably driven by copper in bed sediments, as indicated by water, sediment, and macroinvertebrate tissue data, plus water-quality modeling and toxicology tests (Nimmo et al., 1998). Copper concentrations in bed sediments have remained largely unchanged since 1994 (Fig. 3A), even after estimated 15 yr to 100 yr floods during snowmelt runoff in 1995, 1996, and 1997. The range of Cu concentrations in three duplicate samples at 17 riffles in 1994 mostly encompasses the range measured at the same sites in subsequent years, indicating little change in concentrations due to flood scour and deposition. If Cu influx to bed sediments was primarily from acid drainage, we expect that concentrations would decline during floods, and then increase over subsequent years by adsorption. Furthermore, there was no improvement in macroinvertebrate health following 1992 remediation that reduced acid drainage (Fig. 3B). Copper in Soda Butte Creek bed sediments thus appears to derive primarily from influx of Cu-bearing sediments.

Sources of contaminated sediment include the McLaren ore stockpile (Fig. 1), which erodes into the stream during snowmelt runoff, mine workings in the headwaters, and bank erosion of flood-plain tailings deposits. Along middle and lower Soda Butte Creek, average Cu and Pb concentrations in overbank sediments from recent natural floods are 1.6 and 1.8 times higher than in premining overbank sediments of similar texture on late Holocene fluvial terraces (Table 1); means are different at a probability level (P) of 0.01. Modern sediment metal concentrations thus are not solely natural background levels, but include additional inputs from headwaters mining disturbance.

In the modern channel, 81% of the decrease in sediment Cu concentrations below the McLaren site is explained by a dilution model (Marcus, 1987) that simulates mixing of sediments from contaminated headwaters and Cu-poor downstream tributaries (Fig. 3A). The downstream decrease in Cu is not due to settling of heavy minerals ($\rho > 3.0$ g/cm^3, where ρ is density), which are not significantly correlated to Cu concentrations ($P > 0.10$, $r^2 = 0.02$, $n = 88$). In the dilution process, major floods introduce large amounts of relatively clean sediment, but these are balanced by increased input of contaminated sediments from unremediated mine sites and the flood-plain tailings as well as exposed natural sources in the New World district.

Nowhere below the tailings is the maximum number of macroinvertebrate taxa as high as the minimum number of taxa found at six comparable sites along Pebble Creek, a tributary draining an unmined basin of similar lithology and geomorphic character but little sulfide mineralization (Fig. 1). Above the McLaren complex, the number of taxa is similar to numbers found in Pebble Creek, but falls to near zero below the tailings, followed by a gradual downstream increase (Fig. 3B). The distance below the tailings at which taxa numbers recover has not systematically decreased since 1967, implying continuing contamination along the stream length consistent with our preflood and postflood concentration data and the maintenance of contaminant levels by dilution mixing (Fig. 3A). Although the sediment Cu concentrations in Soda Butte Creek are low relative to most affected streams, tissue Cu concentrations in upper Soda Butte Creek macroinvertebrates are comparable to those in the upper Clark Fork River, Montana, a Superfund site contaminated by sulfide-rich tailings releases. Furthermore, in standard laboratory toxicology tests, significant increases in mortality occurred when the aquatic macroinvertebrate *Hyalella azteca* was exposed to sediments from 10 km below the tailings with Cu concentrations of 30–90 mg/kg (Nimmo et al., 1998, their Fig. 5). Impacts are further indicated by the direct relation of Cu in macroinvertebrate tissue to Cu in bed sediments and the inverse relation of macroinvertebrate taxa counts to Cu in bed sediments (Fig. 4).

PERSISTENCE OF IMPACTS

Previous studies document persistence of mining-related heavy metals in flood-plain sediments over 10–100 yr time scales (reviewed in Miller, 1997). Our data provide additional insights on how geomorphic processes govern the distribution and duration of impacts in Soda Butte Creek and similar abandoned mine settings. In-channel metal concentrations are largely controlled by sediment mixing (Fig. 3A), so even large natural floods will not reduce metal concentrations unless contaminated sediment sources are isolated. Maintenance of metal concentrations by sediment mixing is reflected in spatial patterns of Soda Butte Creek macroinvertebrate populations, which remained essentially unchanged over 30 yr (Fig. 3B). There is no reason to anticipate natural improvements until vegetation can reestablish on barren mine sites and limit erosion, a slow process in harsh alpine and subalpine environments like those of upper Soda Butte Creek (Brown et al., 1976).

Geomorphic processes also control the long-term persistence of impacts in the flood plain. The 1950 dam break emplaced tailings across broad flood plains above the ~100 yr flood stage reached in 1997. Channel lateral erosion removes contaminated flood-plain sediment, but the period required for complete reworking is difficult to estimate given the localized and sporadic channel migration measured in recent floods. Holocene fluvial terraces along lower Soda Butte Creek each preserve overbank sediments ranging in age over several hundred years to >1000 yr (Meyer et al., 1995), indicating the potential residence time of the flood-plain tailings. Metal concentrations currently exceed thresholds for vegetation impacts in tailings deposits along the entire length of Soda Butte Creek, and these effects could persist in some areas for centuries.

RELEVANCE TO OTHER WATERSHEDS

Abandoned mine workings similar to the New World district exist throughout the western United States (U.S. Geological Survey Abandoned Mine Lands Science Team, 1999), as do flood plains contaminated by in-stream tailings disposal (Marron, 1992) and impoundment failures (U.S. Committee on Large Dams, 1994). Many sites feature extensive barren areas or contaminated flood plains that sustain metal-contaminated sediment inputs to streams. The impacts of headwaters mining on the lower Soda Butte Creek aquatic environment are subtle, but their persistence suggests that effects will be long lasting in more severely contaminated streams. The overbank deposition, bank erosion, and in-channel sediment mixing that control metal concentrations and retard recovery in Soda Butte Creek are universal geomorphic processes in fluvial systems (e.g., Helgen and Moore, 1996; Miller, 1997), although rates and styles vary between different environments. The watershed-wide distribution and long-term persistence of mine impacts in Soda Butte Creek are therefore likely to be typical of similar drainages around the world.

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