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Scott A. Lecce , Robert T. Pavlowsky , Gwenda S. Bassett & Derek J. Martin

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METAL CONTAMINATION FROM GOLD MINING IN THE CID DISTRICT, NORTH CAROLINA

Scott A. Lecce

**Department of Geography
East Carolina University
Greenville, North Carolina 27858**

Robert T. Pavlowsky and Gwenda S. Bassett

**Department of Geography, Geology, and Planning
Missouri State University
Springfield, Missouri 65897**

Derek J. Martin

**Department of Geography
University of Tennessee
Knoxville, Tennessee 37996**

Abstract: The purpose of this paper was to assess contamination from 19th century gold (Au) mining in the Cid district, North Carolina. Sediment samples collected from active channel sediments and floodplain cores were analyzed for mercury (Hg), copper (Cu), lead (Pb), and zinc (Zn). Analysis of trace metal concentrations shows that although Hg contamination exists at relatively low levels (i.e., no samples exceeded the probable effect concentration for Hg), the active channel sediments and historical floodplain deposits are contaminated by Hg downstream from all mines in the district. We also found significant contamination by Cu, Pb, and Zn. The use of Hg and other metals as tracers associated with mining activities suggests that long-term rates of floodplain sedimentation in the Cid district (0.3–0.9 cm/yr) were less than half as high as those in the nearby Gold Hill district. This suggests that the intensity of land disturbance in the Cid district was less than in the more intensively mined Gold Hill district. [Key words: gold mining, mercury, trace metal contamination, Cid District, North Carolina.]

INTRODUCTION

Historic mining activities cause a variety of environmental impacts that may persist long after operations have ceased, and many of these impacts can pose serious problems for ecological and human health. One of the most damaging aspects of gold (Au) mining is the use of mercury (Hg) to recover Au from ore-bearing minerals by the amalgamation process, which has led to the release of large amounts of toxic Hg to the environment (Nriagu, 1994). Sulfate-reducing bacteria in aquatic sediments can convert Hg, originally released as inorganic Hg, into the more toxic organic form, methylmercury (MeHg), which can bioaccumulate and biomagnify through aquatic food chains (Gilmour et al., 1992; Holmes and Lean, 2006). The transport and fate of Hg is cause for concern because it is a potent neurotoxin, particularly in prenatally exposed infants (Clarkson, 2002). Nevertheless, much

remains to be learned about the environmental impacts, long-term dispersal, and ultimate fate of Hg (Fitzgerald and Clarkson, 1991; Hylander and Goodsite, 2006). In addition to the release of Hg used in the amalgamation process, Au mining operations may release other contaminants to the environment because Au-bearing ores frequently contain other toxic elements, such as copper (Cu), lead (Pb), and zinc (Zn) (Horowitz et al., 1990; Moore and Luoma, 1990; Axtmann and Luoma, 1991; Horowitz et al., 1993).

The first recorded discovery of Au in the U.S. took place in 1799 in the Piedmont of North Carolina when a 7.7 kg (17 lb) nugget was found in Little Meadow Creek in Cabarrus County (Pardee and Park, 1948; Koschmann and Bergendahl, 1968; Young, 1982; Knapp and Glass, 1999). This stimulated interest and exploration throughout the southern Piedmont gold belt (i.e., from Virginia to Alabama), yet North Carolina produced more Au than any other state in the South, and led the nation in Au production until 1848 (Knapp and Glass, 1999). One of the most intensively mined areas in the southern Piedmont gold belt was the Gold Hill district in southeastern Rowan and northeastern Cabarrus counties (Knapp and Glass, 1999). The district developed rapidly after the principal veins were discovered (Koschmann and Bergendahl, 1968) and Hg was used to amalgamate the finely disseminated Au in vein ore that had been pulverized in Chilean mills (Knapp and Glass, 1999).

In a reconnaissance investigation of Hg contamination in the Gold Hill district, Lecce et al. (2008) found that active channel sediments and floodplain deposits at the mouth of Dutch Buffalo Creek (25 km downstream from the Gold Hill source) are highly contaminated, with a peak Hg concentration (2.2 mg/kg) that is about 35 times greater than their mean background concentration of 0.06 mg/kg. Vertical trends in Hg and Cu concentrations were also used to estimate historical rates of overbank sedimentation on the floodplain, with peak rates of 2.1–2.9 cm/yr occurring during the period of 1842 to 1856. Pavlowsky et al. (2010) quantified the downstream trends of Hg and Cu concentrations within in-channel bar and bench deposits in Dutch Buffalo Creek using two-parameter regression models, consisting of distance from mine source and sand content of the sample, to explain >80% of the variation in sediment-metal concentrations.

The watershed-scale contamination documented at Gold Hill raises the question of whether Hg contamination of sediments is widespread in the North Carolina Au belt and whether Hg is a useful geochemical tracer for evaluating historic sedimentation rates in other parts of the Piedmont. The purpose of this paper, therefore, is to assess contamination from Au mining in several watersheds in the Cid district, about 30 km to the northeast of Gold Hill. Specific objectives are (1) to review the mining history of the Cid District, (2) to evaluate channel and floodplain contamination in watersheds downstream from mines, and (3) to use floodplain profiles to estimate historical sedimentation rates. Although the potential for Hg contamination in mining areas beyond Gold Hill has negative implications for stream ecology and environmental health, the use of Hg and other metals as environmental tracers may allow a more comprehensive evaluation of historical rates of floodplain sedimentation associated with land use change across the region.

BACKGROUND

There is an extensive literature focusing on understanding the physical and geochemical processes in controlling mining sediment transport (e.g., Lewin and Macklin, 1987; Miller, 1997; Macklin et al., 2006; Miller and Orbock Miller, 2007). Because it is common for >90% of metal contaminants in rivers to be transported in the particulate phase (Martin and Meybeck, 1979; Meybeck and Helmer, 1989; Horowitz, 1991), fluvial processes can effectively disperse both mining sediment and associated toxic contaminants long distances downstream (Horowitz et al. 1988, 1990; James 1989, 1991; Knighton, 1989). Metal concentrations in fluvial sediments generally decrease exponentially downstream from mine sources due to the influence of both physical and chemical processes (Wolfenden and Lewin, 1978; Axtmann and Luoma, 1991; Miller and Orbock Miller, 2007). This decay trend is caused by the influence of one or more of the following factors: (1) mixing and dilution with tributary sediment inputs (Marcus, 1987; Marron, 1989), (2) hydraulic sorting that selectively deposits higher density, metal-rich sulfide grains along the channel bed close to the source (Best and Brayshaw, 1985; Day and Fletcher, 1991), (3) removal from transport by deposition of mining sediment in channel bars and overbank floodplain deposits (Bradley, 1989; Pavlowsky, 1996; Lecce and Pavlowsky, 2001; Raab et al., 2010), and (4) release of metals from the particle surface to the water column by weathering and solution of primary sulfides (Reece et al., 1978; Mann and Lintern, 1983).

Spatial patterns of sediment storage in floodplains is highly variable and depends on a variety of factors such as valley width, lateral distance from the channel, floodplain microtopography, local hydraulic conditions, and stream power (Walling and He, 1998; Lecce, 1997; Miller and Orbock Miller, 2007). Floodplains can act as both sources and sinks for mining contaminants (Moore and Luoma, 1990; Lecce and Pavlowsky, 1997; Nanson and Croke, 2002). During the period of mining, >40% of the tailings introduced into a river system may go into storage in floodplain deposits (Jeffery et al. 1988; Marron, 1989, 1992). However, after mine closure, subsequent remobilization of stored mining sediment by bank erosion and weathering can continue to contaminate the river for centuries (Ongley, 1987; Leenaers, 1989; Malmon et al., 2002; Lecce et al., 2008).

Ore milling operations typically supply contaminated sediment to the channel in the form of silt- and sand-sized tailings particles with high concentrations of metals in both mineral and surface-bound forms (Wolfenden and Lewin, 1978; Miller, 1997). Sediment in this size range can be rapidly transported downstream and deposited within channel bar and bench deposits and floodplain overbank and splay deposits during floods (Horowitz et al., 1988; Moore and Luoma, 1990). Coincidentally, periods of both peak mining activity and initial land use disturbance during agricultural settlement occurred simultaneously in some watersheds in the Midwest and Southeast regions of the United States (Knox, 1987, 2006; Jacobson and Coleman, 1986; Leigh, 1994; Lecce and Pavlowsky, 2001; Lecce et al., 2008). Thus, sedimentation and mass storage rates of contaminated sediment were enhanced by more widespread and/or intensive land-use changes that increased upland sediment supply and overbank flood frequency within the watershed due to causes

not necessarily related to mining contamination sources (Knox, 1977; Leigh, 1994; Trimble, 2008).

Although it is well established that studies of contaminated mining sediment deposits are important for predicting and regulating potential toxic effects of metals within the aquatic environment (Marcus, 1989), records of mining contamination in the form of geochemical profiles in floodplain cores can also be used as stratigraphic tracers to quantify historical and recent sedimentation trends within watersheds (e.g., Knox, 1987, 2006; Macklin and Klimek, 1992; Lecce and Pavlowsky, 2001). The most effective mining sediment tracers for chemostratigraphic analyses have the following characteristics: (1) sediment-borne inputs occur at relatively high concentrations and loads compared to uncontaminated sediment transport, (2) records of mine location and production history are well-documented, (3) mining periods coincide with or bracket critical land use change episodes and/or geomorphic adjustments, (4) rates of alluvial sediment and tracer storage are high, (5) the potential for post-depositional geochemical mobility is low, and (6) the contamination record can be evaluated at sufficient sampling precision necessary to detect source and environmental variations. Mining tracer methods have been applied in floodplain studies within watersheds of >5 km² in area with a temporal resolution of ± 10 years to detect overbank floodplain sedimentation rates from <0.1 cm/yr to >3 cm/yr (Knox, 1987; Leigh, 1994; Lecce and Pavlowsky, 2001; Bain and Brush, 2005; Lecce et al., 2008). More recently, isotopic tracers (especially Pb) have also been used successfully to date units and to determine source and dispersal pathways for trace metals in floodplains (Hudson-Edwards et al., 1999; Miller et al., 2002; Villarroel et al., 2006; Miller and Orbock Miller, 2007).

STUDY AREA

European settlement of the Piedmont in North Carolina began around 1740 and, by the early 1800s, the agricultural economy in Davidson County was thriving with corn, wheat, cotton, and tobacco as the primary crops (McCachren, 1994). The Cid mining district covers an area of about 325 km² in southern Davidson County, extending from the Yadkin River in the southwest to a couple kilometers beyond the village of Cid in the northeast (Koschmann and Bergendahl, 1968) (Fig. 1). The mines of the Cid district are located in the fine-grained metasedimentary and metavolcanic rocks of the Carolina slate belt. In addition to Au, this district was an important source of Cu, Ag (silver), Pb, and Zn (Carpenter, 1976). Although Carpenter (1976, p. 45) noted that Au was first worked in this district before 1824, the earliest record of significant production was in 1832 at the Conrad Hill mine (Pardee and Park, 1948). Mining was at its peak in the district from 1838 to 1862 and from 1875 to 1885 (Carpenter, 1976). The last mine closed in 1907 at the Emmons Mine (Pardee and Park, 1948). Trimble's (2008) maps of average depth of soil loss (estimated by an analysis of soil profile truncation) show that soil loss in Davidson County ranged from 11 cm to 18 cm during the peak period of "erosive land use" from 1860 to 1920.

The streams in the study area are typically characterized by riffle-pool channels that form a sinuous to meandering planform. Locally, outcrops of bedrock or

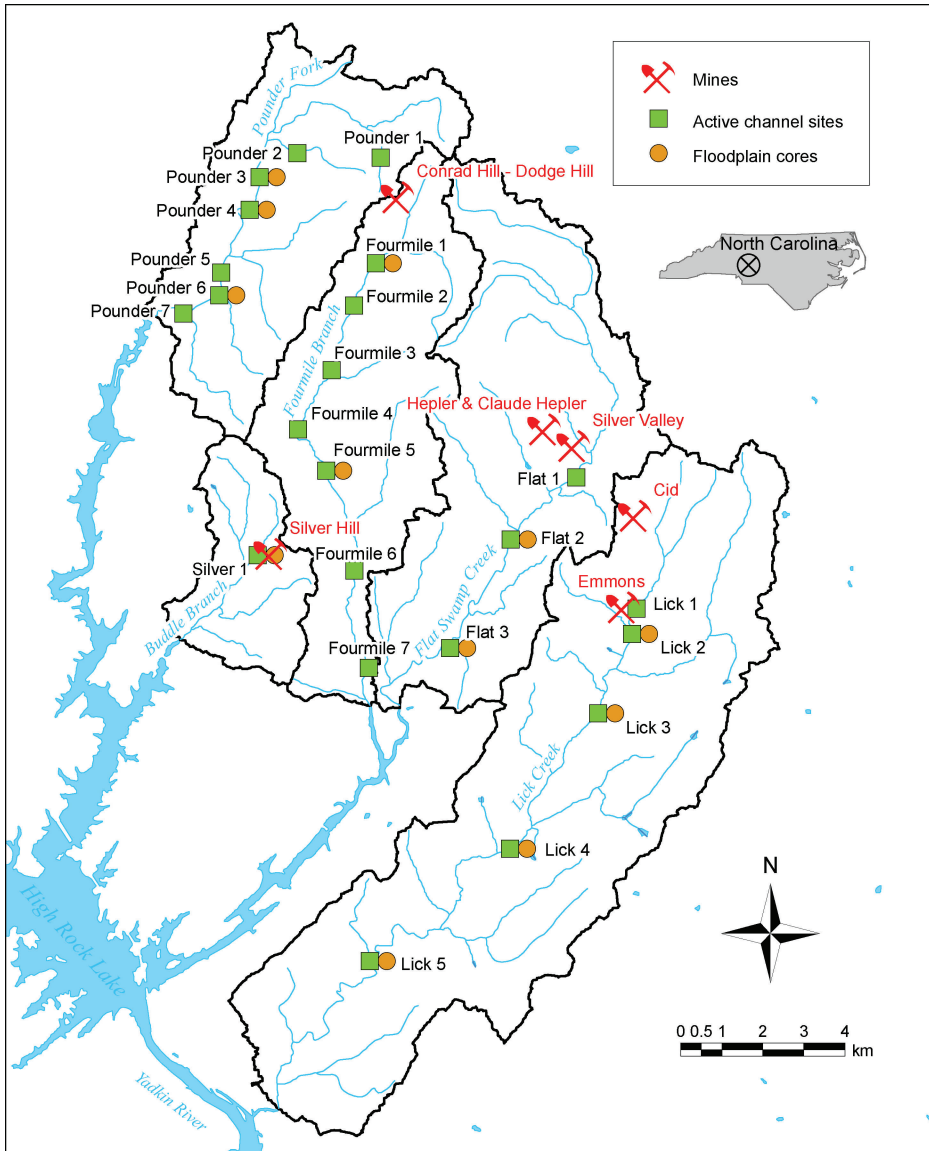


Fig. 1. Study area and sample site locations.

resistant clayey residuum may limit bed adjustments or produce riffles. Most of the floodplains studied consist of silt loams mapped as the Oakboro series with the more loamy Chewacla series occurring in the northwestern part of the study area along Pounder Fork and Buddle Branch (McCahren, 1994). Both of these soil series form in recent alluvium on floodplains and are classified as Fluvaquentic Dystrochrepts.

The floodplains are typically composed of vertically accreted silty overbank sediment that overlies sandy or gravelly laterally accreted channel deposits of varying thickness. In some places, the coarse channel deposits were absent in cutbank exposures and, in others, they formed almost two-thirds of the floodplain unit, particularly in smaller tributaries.

METHODS

We selected five streams that had the potential to be contaminated from runoff and sediment from mining areas. Pounder Fork, Buddle Branch, Fourmile Branch, and Flat Swamp Creek flow into High Rock Lake, a reservoir on the Yadkin River, while Lick Creek enters the Yadkin River downstream from the reservoir (Fig. 1). Background metal concentrations were assessed by collecting single grab samples at 16 soil exposures and 43 active channel sites in areas not influenced by mining activities (Pardee and Park, 1948; Knapp and Glass, 1999). In areas downstream from mines, we collected a total of 84 samples from active channel sediments along 23 reaches (Fig. 1). These samples were collected just above the low water line from the tail ends of alternate or point bars where fine sediments were deposited during recent flows, using a noncontaminating shovel, and they were placed in labeled quart-size plastic freezer bags. A total of 37 floodplain cores were collected at 12 sites using a 2-cm diameter Oakfield soil probe. We collected composite samples from the cores in intervals that ranged from 5 cm to 20 cm in thickness, depending on the stratigraphy. Geochemical and physical analyses were performed on selected cores.

Sample preparation and physical analysis was carried out at the Water and Soil Laboratory of the Ozarks Environmental and Water Resources Institute at Missouri State University following standard methods and operation procedures (OEWRI, 2011). Sediment samples from the field were dried, disaggregated with mortar and pestle, and passed through a 2 mm sieve to remove fine gravel and organic materials. Geochemical analyses were conducted on the <2 mm fraction by a commercial laboratory (ALS Chemex, Sparks, NV, USA) where the samples were prepared using an aqua-regia extraction (hot 3:1 nitric-hydrochloric acids) (Mudroch et al., 1997). Hg levels were determined using cold vapor atomic absorption spectroscopy (AA), while 33 additional elements were analyzed by inductively coupled plasma-atomic emission spectroscopy (ICP-AES). Lower detection limits are 0.01 mg/kg for Hg, 1 mg/kg for Cu, and 2 mg/kg for Pb and Zn. ALS Chemex follows quality control procedures involving both batch check standards and duplicate analyses on every 10–20 samples. Duplicate sample analyses are typically within 10%. We have also previously submitted triplicate geochemical standard materials available from the United States Geological Survey to ALS Chemex and found that the coefficient of variation values is less than 15%. Because this was a reconnaissance study, we did not collect duplicate samples to determine sampling precision. Therefore, we emphasized collecting samples from a larger number of sites rather than duplicate samples from the same site. Nevertheless, our previous experiences with core profiles at Gold Hill and elsewhere suggest that, while the absolute concentrations at similar core depths may vary from core to core, profile trends remain relatively consistent

with background and peak inflections occurring at similar depths. Although metal concentrations in several cores demonstrated a significant negative relationship with the percentage of sand, comparison of sand normalized concentrations (Horowitz, 1991) with total element concentrations indicated that grain size exerts a minimal influence on metal trends in the cores.

RESULTS

Background Concentrations

We used several techniques to determine whether sediments have been contaminated by mining. First, we sampled soils and sediments in the Cid district that were not contaminated by mining activities (Table 1). The mean background concentration for Hg is 0.05 mg/kg, while means for Cu, Pb, and Zn range from about 25 to 50 mg/kg. These mean concentrations are similar to background levels found globally in soils (Reimann and Caritat, 1998), in the National Geochemical Survey for Davidson County (USGS, 2004), and by Lecce et al. (2008) in the Dutch Buffalo watershed in nearby Cabarrus County. Second, we used the iterative 2σ technique (Matschullat et al., 2000) to obtain the following contamination thresholds: Cu = 52 mg/kg, Hg = 0.07 mg/kg, Pb = 29 mg/kg, and Zn = 70 mg/kg. Third, in some cases background concentrations in individual cores were lower than our calculated mean background concentration (Table 1). In these cases we determined that contamination existed when the lower portions of the core were overlain by a distinct increase in metal concentrations even if that increase did not exceed the contamination threshold identified using the iterative 2σ technique.

Fourmile Branch/Pounder Fork

The Conrad Hill/Dodge Hill mines are located near the drainage divide between Fourmile Branch and Pounder Fork. These mines were originally mined for Au in the early 1830s, and then Cu as the mine shafts deepened (Carpenter, 1976). Closed after 1853, the mine was reopened from 1880–1884. With several deep shafts, this is the second largest mine complex in the Cid district in terms of estimated total production. Nitze and Wilkins (1897) reported that there was evidence of the use of stamp mills and amalgamation, but it is not clear whether these activities took place on site.

Believing that mine waste from these mines was most likely dispersed to the southeast, we collected a number of active channel and floodplain samples along Fourmile Branch and just two active channel samples from Pounder Fork in 2007. Table 2 shows that along Fourmile Branch there is little contamination in either the active channel or the floodplain sediments. Of the 29 samples collected from the active sediments, the three highest Hg concentrations of only 0.10–0.12 mg/kg were found at the site closest to the mine source (Fourmile 1) (Fig. 2). Active channel sediments are uncontaminated by Cu, Pb, and Zn.

One of the floodplain cores at the site closest to the mines (Fourmile 1–50) suggests possible low level Hg contamination in the upper 40 cm (Fig. 3). The remaining

Table 1. Background Concentrations

		Cu (mg/kg)	Hg (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
All (<i>n</i> = 64)					
	Mean	34	0.05	24	49
	Median	30	0.05	22	46
	SD	17	0.03	11.5	19
	Range	11–79	0.01–0.14	10–74	18–101
Surface soils (<i>n</i> = 9)					
	Mean	44	0.08	32	65
	Median	43	0.06	30	68
	SD	19	0.04	6.9	23
	Range	20–77	0.02–0.14	24–46	40–101
Subsurface soils (<i>n</i> = 7)					
	Mean	51	0.06	19	48
	Median	45	0.03	18	41
	SD	15	0.05	5.4	23
	Range	37–79	0.01–0.14	13–28	26–96
Active channel (<i>n</i> = 43)					
	Mean	31	0.05	23	47
	Median	28	0.05	20	40
	SD	16	0.02	13	18
	Range	11–75	0.02–0.11	10–74	18–91
Surface floodplains/terraces (<i>n</i> = 5)					
	Mean	20	0.06	26	42
	Median	19	0.05	23	46
	SD	6.5	0.03	9.4	11
	Range	13–30	0.03–0.10	18–42	27–56
Mean, Davidson County ^a		17	0.034	28	50
Mean, global for soil ^b		25	0.05	17	70
Mean, Gold Hill ^c		35	0.06	21	77

^aMean value (*n* = 5) reported in the National Geochemical Survey for Davidson County, North Carolina (USGS, 2004).

^bReimann and Caritat (1998).

^cLecce et al. (2008).

floodplain samples along Fourmile Branch are uncontaminated. Given the low level of contamination and its confinement to the headwaters of Fourmile Branch, it is likely that only a small proportion of metals from the mines were transported to the east. However, the two active channel samples collected at Pounder 1 on the west

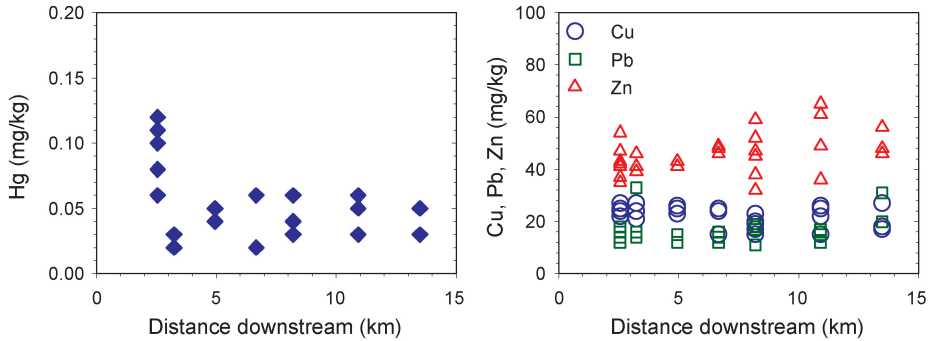


Fig. 2. Downstream changes in active channel metal concentrations, Fourmile Branch.

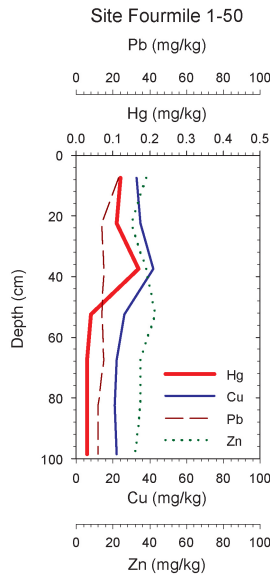


Fig. 3. Floodplain metal concentrations at Fourmile 1-50.

side of the drainage divide showed high concentrations of Cu (283 mg/kg and 314 mg/kg) and Hg (0.32 mg/kg and 0.40 mg/kg). Therefore, we returned in 2008 to do some more extensive sampling along Pounder Fork.

Figure 4 shows that Hg concentrations in the active channel sediments decrease downstream, with 8 of the 12 samples contaminated at levels greater than 0.12 mg/kg. The high Cu concentrations are limited to the upstream Pounder 1 site and, with the exception of one anomalously high Zn concentration (372 mg/kg) at Pounder 6, Pb and Zn concentrations within active channel sediments were not distinguishable from background values.

Pb and Zn concentrations in floodplain sediments along Pounder Fork are at background levels, but all of the overbank cores are contaminated by Hg at levels

Table 2. Active Channel and Floodplain Metal Concentrations, Cid Mining District

	Active channel					Floodplain				
	Cu (mg/kg)	Hg (mg/kg)	Pb (mg/kg)	Zn (mg/kg)		Cu (mg/kg)	Hg (mg/kg)	Pb (mg/kg)	Zn (mg/kg)	
Fourmile Branch										
Mean	22	0.05	16	46		26	0.05	16	30	
Median	23	0.05	16	46		24	0.04	13	30	
SD	3.9	0.03	5.1	7.8		10	0.03	15	8.0	
Range	15–27	0.02–0.12	11–33	32–65		18–85	0.02–0.17	8–100	19–58	
<i>n</i>	29	29	29	29		44	44	44	44	
Pounder Fork										
Mean	71	0.14	11	71		31	0.20	9.3	28	
Median	34	0.12	10	48		30	0.15	9.0	27	
SD	97	0.10	3.7	88		11	0.14	2.9	7.4	
Range	13–314	0.05–0.40	4–18	20–372		13–59	0.05–0.62	3–17	14–46	
<i>n</i>	14	14	14	14		89	89	89	89	
Buddle Branch										
Mean	41	0.10	114	1118		16	0.05	55	124	
Median	34	0.10	110	1190		15	0.04	23	63	
SD	16	0.02	18	266		5.2	0.03	50	161	
Range	32–73	0.08–0.14	100–150	608–1320		40780.0	0.01–0.11	13–171	23–650	
<i>n</i>	6	6	6	6		28	28	28	28	

Flat Swamp Creek

Mean	25	0.16	182	337	26	0.09	86	134
Median	25	0.12	116	293	25	0.07	43	94
SD	33	0.13	105	268	9.6	0.07	95	95
Range	14-38	0.05-0.41	80-452	143-617	14-75	0.01-0.28	16-439	27-358
<i>n</i>	13	13	13	13	39	39	39	39

Lick Creek

Mean	42	0.06	24	65	27	0.04	14	35
Median	30	0.06	24	70	14	0.04	12	31
SD	27	0.03	6.8	19	31	0.02	5.1	12
Range	13-94	0.02-0.12	16-49	32-90	7-155	0.01-0.10	9-36	19-78
<i>n</i>	20	20	20	20	99	99	99	99

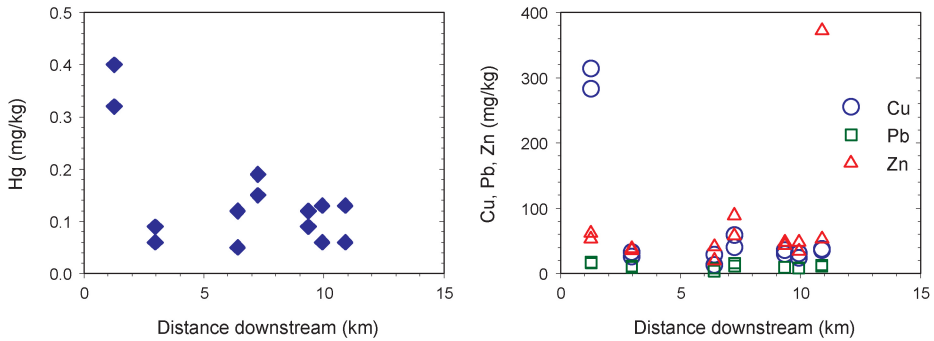


Fig. 4. Downstream changes in active channel metal concentrations, Pounder Fork.

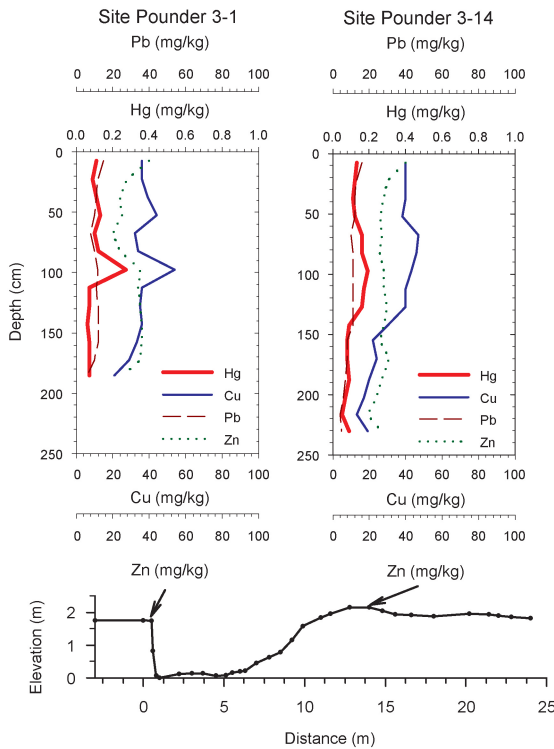


Fig. 5. Floodplain metal concentrations and valley cross section at Pounder 3.

above 0.10 mg/kg. Pounder 3–14 displays a weak signal, suggesting the onset of mining activities at a depth of about 150 cm where Hg and Cu levels increase above background concentrations (Fig. 5). The entire unit is contaminated by Hg at Pounder 4–6 and Pounder 4–27.5 (Fig. 6). The highest floodplain Hg concentration measured in the Cid district of 0.62 mg/kg (Table 2) occurs at Pounder 6–16.3. This

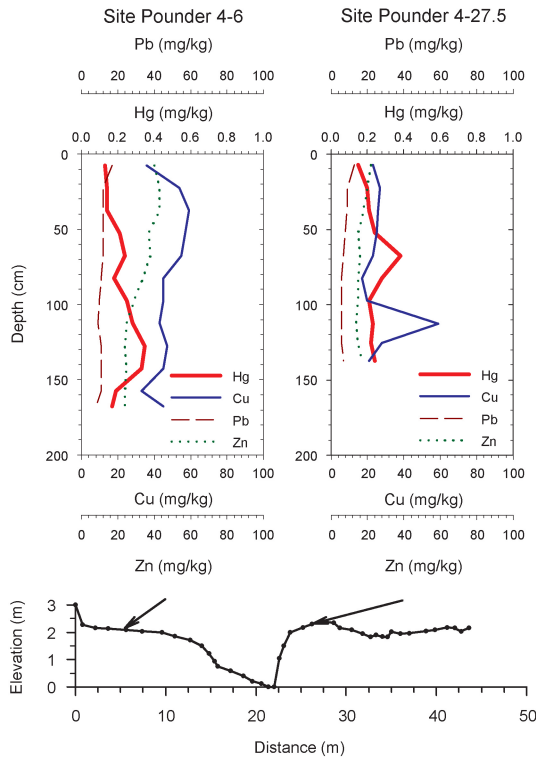


Fig. 6. Floodplain metal concentrations and valley cross section at Pounder 4.

core provides a good mining signal with concentrations in the lower portion of the core at background levels (0.05–0.1 mg/kg) before increasing abruptly at a depth of about 100 cm (Fig. 7). The sampling along Pounder Fork indicates that most of the contaminants from the Conrad Hill/Dodge Hill mines were dispersed to the west. Contamination by Hg is the highest observed in the Cid district, and there is some low-level contamination by Cu.

Buddle Branch

The Silver Hill mine was one of the few in the southern Piedmont gold belt that was not operated primarily for Au, but rather for Ag, Pb, and Zn (Pardee and Park, 1948). Discovered in 1838 (Nitze and Wilkins 1897), it was worked until 1882 and was the largest mine in the district in terms of total production (Pardee and Park, 1948). Although Hg has also been used to extract Ag by amalgamation (Nriagu, 1994), historical records do not indicate whether Hg was used at the Silver Hill mine.

Access could only be obtained at one site along the short length of Buddle Branch that drains from the mine site. Cu concentrations are at background levels, but both the active channel and floodplain sediments have low-level Hg contamination and

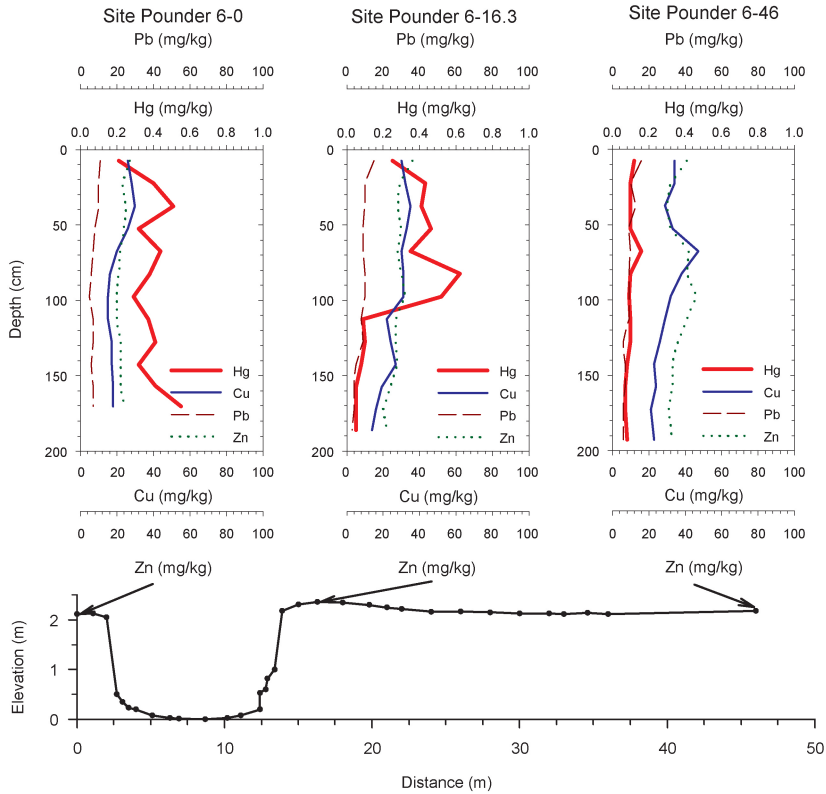


Fig. 7. Floodplain metal concentrations and valley cross section at Pounder 6.

very high concentrations of Pb and Zn (Table 2; Fig. 8). Four active channel samples with Hg levels between 0.10 mg/kg and 0.14 mg/kg suggest that the amalgamation process was used to extract Ag. Active channel sediments are much more highly contaminated by Pb and especially Zn than the floodplain sediments, which could indicate that a tailings source continues to supply the channel with contaminated sediments. Cores in the lower floodplain surface (at Silver-15 and Silver-20) show Pb concentrations increasing from near background at about 25 mg/kg in the lower portion to peaks of 140–170 mg/kg. Zn levels in the lower surface are above background throughout, increasing from about 100 mg/kg to peaks that exceed 600 mg/kg near the surface. Pb concentrations in the upper floodplain surfaces on both sides of the channel increase toward the surface in the upper 20–30 cm of each core.

Flat Swamp Creek

Flat Swamp Creek drains the Silver Valley mine (Au, Ag, Pb, and Zn) and a small prospect (Hepler and Claude Hepler mine) with no record of production (Carpenter 1976). The Silver Valley mine was first discovered in 1880 and worked periodically until it closed in 1893. There is some historical evidence for the use of Hg, as Nitze

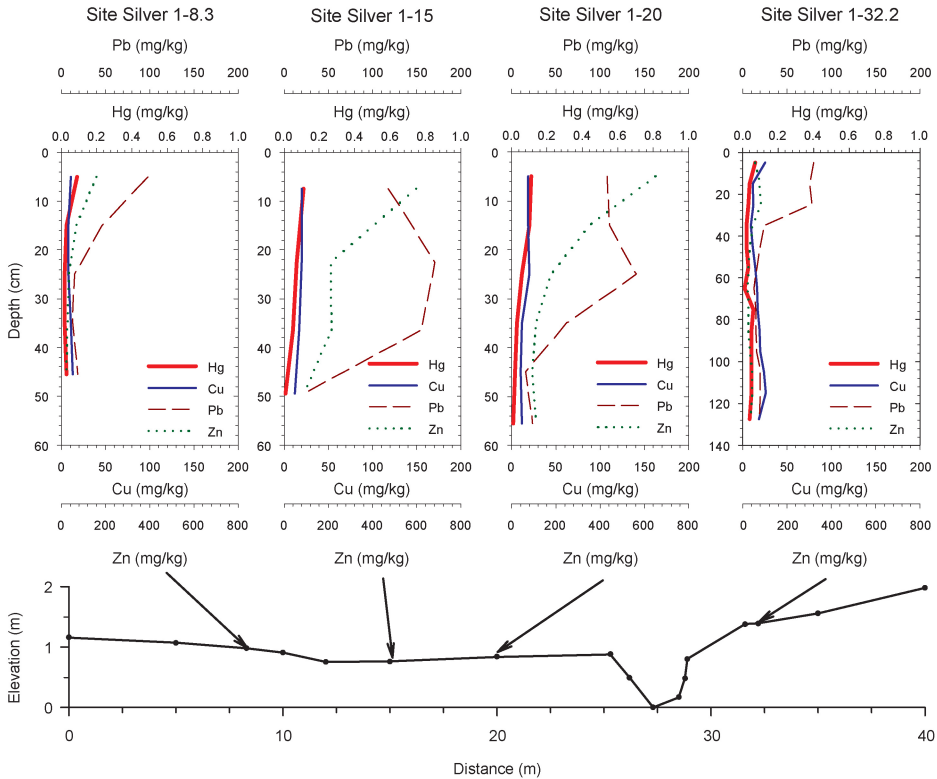


Fig. 8. Floodplain metal concentrations and valley cross section at Silver 1.

and Wilkins (1897) reported that in 1896 amalgamating tables and rockers were used on placer deposits.

The active channel sediments are contaminated above background levels by Hg, Pb, and Zn, with concentrations decreasing downstream from the mine source (Fig. 9). The site closest to the mine source (Flat 1) has the highest active channel Hg concentration measured in the district (0.41 mg/kg), and all but two of the active channel samples have concentrations above background. Overbank samples collected at a cut bank exposure (Flat 2-RB) and two cores in the floodplain surface at Flat 3 provide an excellent mining signal with elevated concentrations of Hg, Pb, and Zn (Fig. 10). The terrace surface (2.3 m above the channel bed) at Flat 3 is capped with 20–30 cm of contaminated sediment.

Lick Creek

The Emmons and Cid mines lie in the headwaters of Lick Creek and were both worked for Au and Cu. The date of initial activities is unknown, but the Emmons mine was reportedly worked extensively both before and after the Civil War (Pardee and Park 1948). According to Carpenter (1976), the mine was reopened and worked

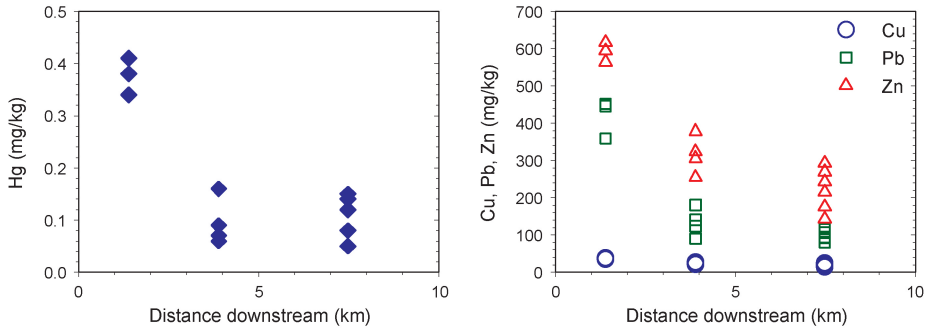


Fig. 9. Downstream changes in active channel metal concentrations, Flat Swamp Creek.

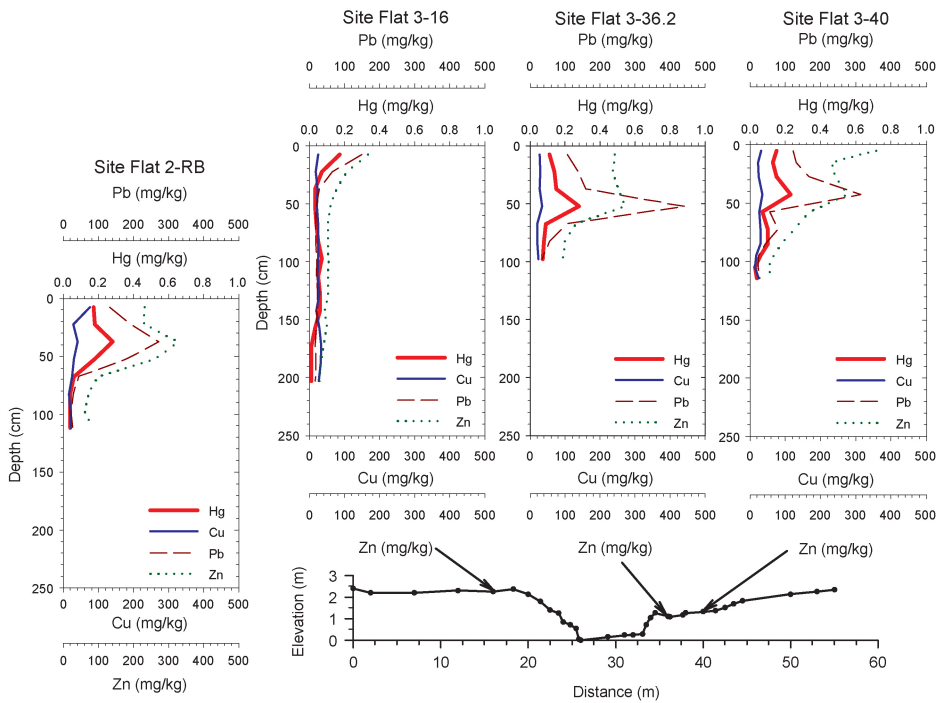


Fig. 10. Metal concentrations in Flat 2 core (left), and floodplain metal concentrations and valley cross section at Flat 3 (right).

for a few years shortly after Civil War, and operated in 1885–1886. The last recorded production was in 1906–1907 (Pardee and Park 1948). The Cid mine was worked periodically for a few years after its discovery in 1882, initially for Au, but later mostly for Cu (Carpenter 1976).

The overall level of metal contamination from mining activities in the Lick Creek watershed is relatively low. The active channel sediments show low levels of

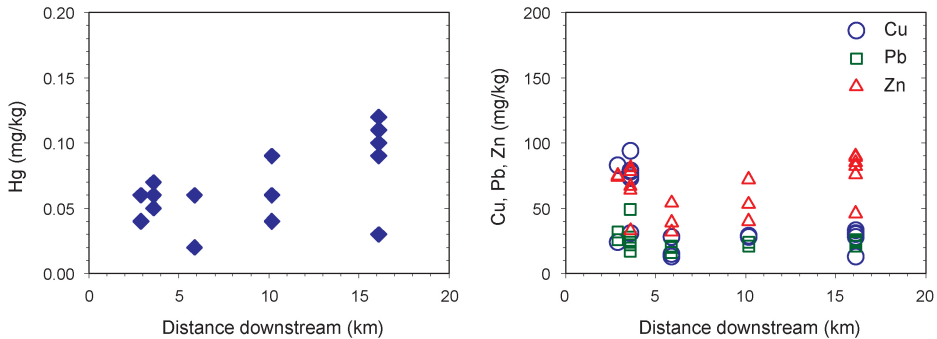


Fig. 11. Downstream changes in active channel metal concentrations, Lick Creek.

contamination by Hg, Cu, and Zn (Fig. 11), with the four highest Hg concentrations occurring at the site farthest downstream from the mines (Lick 5). Nevertheless, Hg concentrations in these samples are comparatively low at 0.09–0.12 mg/kg. Similarly, four of the six samples at Lick 5 had higher Zn concentrations (76–90 mg/kg) than any of the samples collected at Lick 1 or Lick 2. Five samples from Lick 1 and Lick 2 also demonstrated low level contamination by Cu (73–94 mg/kg).

The most significant contamination in the Lick Creek watershed occurs in the floodplain sediments, where two of the cores near the mines at Lick 2 are contaminated throughout with the highest Cu concentrations we found in Cid district floodplains (86–155 mg/kg) (Fig. 12). However, only 3 of 99 samples from 11 cores showed any evidence of Hg contamination, and none with a concentration exceeding 0.09 mg/kg. The source of the Hg and Zn in the active channel sediments at Lick 5 is puzzling given that we did not find elevated concentrations for these metals in the floodplain deposits. This could indicate that some ore processing took place some distance from the mine sites, perhaps even using ore obtained from other watersheds. Although historical accounts do not suggest that Zn was even targeted for mining in this watershed, sphalerite (ZnS) was one of the minerals that accompanied the chief ore mineral, chalcopyrite (Pardee and Park, 1948; Carpenter, 1976).

Sedimentation Rates

Sedimentation rates on floodplains depend on many factors such as floodplain topography, inundation frequency, distance from the channel, overbank flow patterns, and floodplain vegetation characteristics (Miller and Orbock Miller, 2007). Microtopography on floodplain surfaces may have a complex influence on depositional patterns (Steiger et al., 2001), and although sedimentation rates generally decrease with distance from the channel, rates may exhibit considerable spatial variability (Walling and He, 1998). Rumsby (2000) has further shown that vertical accretion rates measured as depths can be quite different from those estimated as volumes. Nevertheless, because volumetric measurements are much more difficult to obtain, vertical accretion rates have traditionally been expressed as the thickness of sediment deposited during a specified time period (Miller and Orbock Miller, 2007).

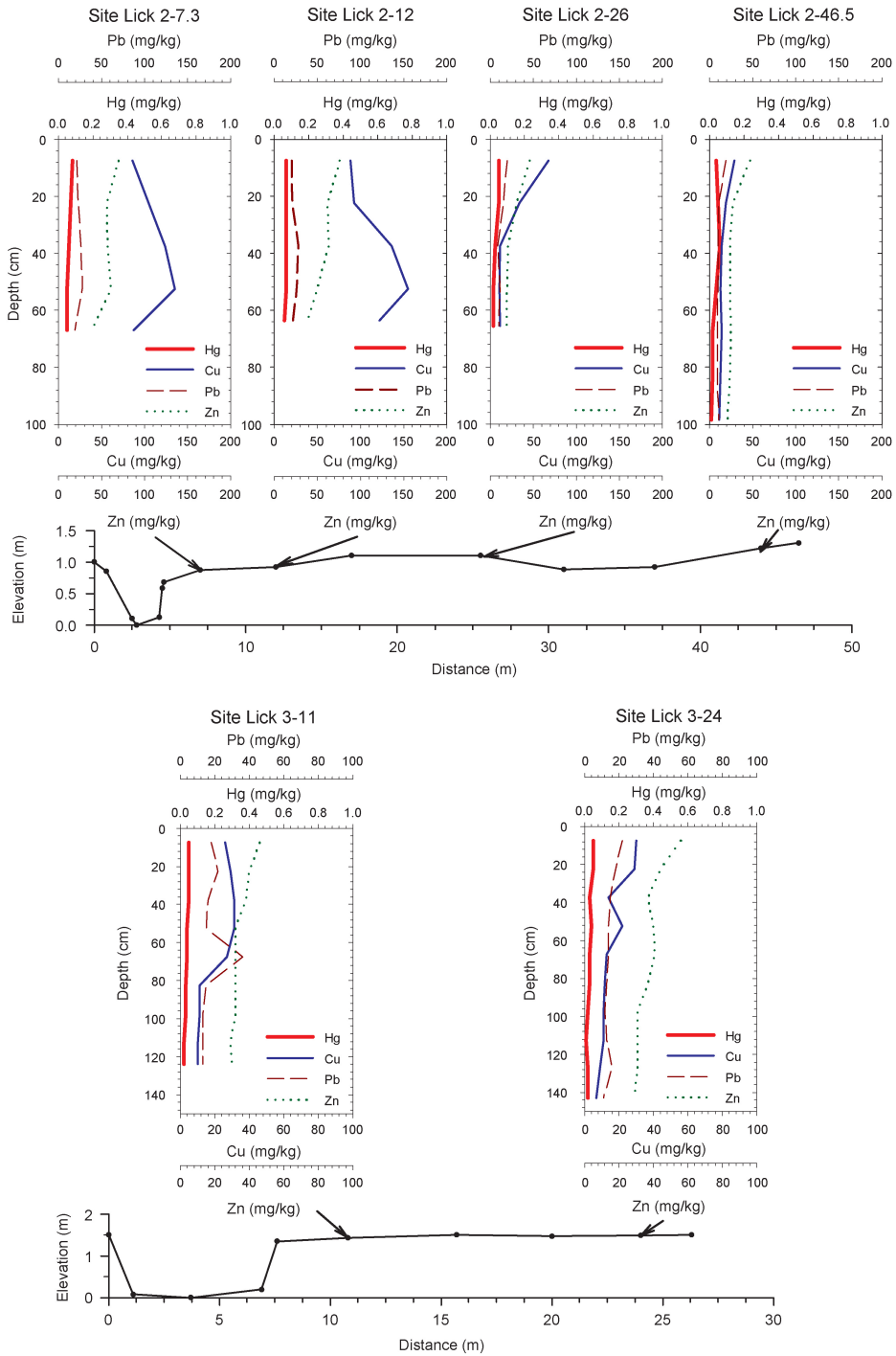


Fig. 12. Floodplain metal concentrations and valley cross sections at Lick 2 and Lick 3.

Although overall metal concentrations are generally low in the Cid district, each watershed is contaminated to some degree and trends in vertical accretion deposits in several of the floodplain cores allow us to estimate historical rates of overbank floodplain sedimentation. These estimates, however, are subject to several sources of error. In addition to the large sampling interval in the cores and in some cases ambiguity in the date that mining began introducing contaminated sediments, our sedimentation rates assume a uniform rate of deposition even though long-term sedimentation rates averaged for the entire period following the initiation of mining activities are probably considerably different than short-term sedimentation rates (Knox, 1989; Lecce and Pavlowsky, 2001). For example, at Gold Hill the mean rate of 2.9 cm/yr during the period of greatest Au production (1842–1856) is about twice the long-term (1842–2006) average of 1.3 cm/yr (Lecce et al., 2008). We also assume that metals were transported immediately from the mine sources to the floodplain, although there may have been a lag between the date of initial mining and initial deposition on the floodplain.

Given these limitations, our approach was to report a range of rates calculated using a variety of assumptions regarding the concentrations we considered as contaminated, the depth at which sediments become contaminated (i.e., the top, bottom, or mid-point of the sampling interval), and the date of initial mining activities. Because the date of initial activities at the Emmons mine is unknown, in order to estimate sedimentation rates in the Lick Creek watershed we chose several dates that corresponded to the earliest reported mine activities in the Cid district (1832), an intermediate period of activity at Emmons and the initial discovery of the Cid mine (1882), and the last recorded production at Emmons in 1907.

Our estimates of long-term sedimentation rates in the Cid district are all less than 1 cm/yr (Table 3). Not surprisingly, rates experienced on terraces that are flooded less frequently are less than those on lower surfaces. Excluding the higher surfaces, long-term sedimentation rates range from 0.3 cm/yr to 0.9 cm/yr with a mean of 0.5 cm/yr. The highest mean rates were located downstream from the Conrad Hill/Dodge Hill mines along Pounder Fork (0.7 cm/yr), while Buddle Branch downstream from the Silver Hill mine had the lowest mean rates at 0.3 cm/yr. These rates are conservative estimates because we cannot be certain that sedimentation began precisely when the mines opened.

DISCUSSION

With maximum concentrations of 0.41 mg/kg in the active channel sediments and 0.62 mg/kg in the floodplain deposits, the overall level of Hg contamination associated with gold mining in the Cid district is relatively low. For comparison, Miller et al. (1998) found mean Hg concentrations of about 100 mg/kg (maximum = 887 mg/kg) in historical valley fill downstream from Au and Ag mines associated with the Comstock Lode near Virginia City, Nevada. At the largest Hg mine in the world (Almadén district, Spain), Higuera et al. (2006) found mean Hg concentrations of 604 mg/kg (maximum = 8889 mg/kg) in soils and 19.5 mg/kg (maximum = 16,000 mg/kg) in stream sediments.

Table 3. Cid District Sedimentation Rates

Site	Mining begins	Signal	Rate (cm/yr)
Pounder 3-1	1832	Hg	0.51-0.60
Pounder 3-14	1832	Hg, Cu	0.68-0.77
Pounder 6-16.3	1832	Hg	0.60-0.85
Silver 1-15	1838	Pb, Zn	0.18-0.25
Silver 1-20	1838	Pb	0.12-0.36
Silver 1-8.3 ^a	1838	Pb, Zn	0.06-0.12
Silver 1-32.2 ^a	1838	Pb, Zn	0.12-0.18
Flat 2-RB	1880	Hg	0.35-0.59
Flat 3-16a	1880	Hg, Pb, Zn	0.12-0.23
Flat 3-36.2	1880	Hg, Pb, Zn	0.35-0.83
Flat 3-40	1880	Hg, Pb, Zn	0.27-0.70
Lick 3-11	1832, 1882, 1907	Cu	0.34-0.74
Lick 2-7.3	1832, 1882, 1907	Cu	0.34-0.73
Lick 2-12	1832, 1882, 1907	Cu	0.34-0.66

^aHigher floodplain/terrace surface.

Table 4. Comparison of Maximum Metal Concentrations in the Cid and Gold Hill Districts

	<i>n</i>	Cu (mg/kg)	Hg (mg/kg)	Pb (mg/kg)	Zn (mg/kg)
Active Channel					
Cid	82	314	0.41	587	1320
Gold Hill ^a	140	1300	36	130	457
Floodplain					
Cid	299	155	0.62	439	650
Gold Hill ^a	783	527	15	143	285

^aLecce and Pavlowsky (unpublished data).

Substantial differences in metal contamination exist between the Cid and Gold Hill mining districts (Table 4). The highest concentrations at Gold Hill were for Hg and Cu, while in the Cid district the highest concentrations were for Pb and Zn. Even though the original exploration in the Cid mining district was for Au, the overall magnitude of Hg contamination is low when compared to Gold Hill. This probably suggests either that the Au mining operations were not very intense (certainly not as intense as the activities at Gold Hill) and/or much less Hg was used. Instead,

Table 5. Comparison of Samples and Sediment Quality Guidelines in the Cid and Gold Hill Districts (percent)

	Cu	Hg	Pb	Zn
Cid (<i>n</i> = 381)				
Above PEC ^a	1	0	5	3
Below TEC ^b	77	88	86	89
Gold Hill (<i>n</i> = 923)				
Above PEC ^a	15	11	0.3	0
Below TEC ^b	26	65	92	95

^aProbable effect concentration (i.e., above which harmful effects are likely to be observed): Cu = 149 mg/kg, Hg = 1.06 mg/kg, Pb = 128 mg/kg, Zn = 459 mg/kg.

^bThreshold effect concentration (i.e., below which harmful effects are unlikely to be observed): Cu = 31.6 mg/kg, Hg = 0.18 mg/kg, Pb = 35.8 mg/kg, Zn = 121 mg/kg.

the highest concentrations found in the Cid district are for Pb and Zn which were present as a byproduct in the ore materials during active mining for Au, but were also identified as the primary metals targeted by these mining operations when Au production did not meet expectations. In contrast, the secondary contamination at Gold Hill is from Cu which was present in the Au ore materials when Au extraction was the goal, and later targeted specifically for recovery.

The overall magnitude of the contamination can also be assessed by comparing our metal concentrations to numerical sediment quality guidelines (SQGs) for freshwater ecosystems. MacDonald et al. (2000) developed two SQGs, a threshold effect concentration (TEC; below which adverse effects are not expected to occur) and a probable effect concentration (PEC; above which adverse effects are expected to occur more often than not), that provide an accurate basis for predicting the presence or absence of sediment toxicity. Table 5 shows that sediment in the Cid district is less contaminated than Gold Hill with only 1–5% of the 381 samples exceeding the PEC for Cu, Pb, and Zn. No samples came close to the PEC for Hg of 1.06 mg/kg. Although just 3 of the 923 samples collected at Gold Hill exceeded the PEC for Pb (and none for Zn), a much larger proportion of the samples (11–15%) had concentrations greater than the PECs for Cu and Hg.

Previous studies have reported Holocene sedimentation rates that vary from 0.02 cm/yr to 0.65 cm/yr (see summaries from Ferring [1986] and Orbock Miller et al. [1993]), and historical rates that may be as high as 15 cm/yr (Trimble and Lund, 1982). In the nearby, but relatively steep terrain of the southern Blue Ridge Mountains of western North Carolina, Leigh and Webb (2006) reported Holocene rates of 0.03–0.08 cm/yr and historical rates of 0.58–0.65 cm/yr that are similar in magnitude to lower relief regions of the southern U.S. that have been more heavily impacted by agriculture (Costa, 1975; Brackenridge, 1984; Jacobson and Coleman, 1986; Trimble, 2008). With a mean of about 0.5 cm/yr, the rates estimated in the Cid district are similar to Leigh and Webb's (2006) historical rates and an order of

magnitude higher than their Holocene rates, but about half the post-mining rates experienced at Gold Hill (Lecce et al., 2008). Differences in sedimentation rates between the Cid and Gold Hill district are not due to differences in channel adjustment since neither area shows evidence of significant bed aggradation or incision. Elsewhere in the southeastern Piedmont, Leigh (1994) found in the Dahlonega gold belt of north Georgia that long-term (1829–1850 to 1994) historical sedimentation rates of 1–3 cm/yr were considerably higher than modern (last 30 yr) rates of about 0.3 cm/yr. Sedimentation rates at Dahlonega and Gold Hill are comparable, but about two to three times higher than those in the Cid district. This is probably explained by the overall greater intensity of mining activity and landscape disturbance at Dahlonega and Gold Hill. For example, beginning in 1868, hydraulic mining was employed at Dahlonega to wash vast quantities of saprolite into sluices (Pardee and Park, 1948; Leigh, 1994). Knapp and Glass (1999) described significant land cover disturbances associated with the mining activities at Gold Hill that would have likely introduced large quantities of sediment to stream systems at the same time that increased sediment delivery from agricultural activities was occurring. Sedimentation rates obtained for the Cid district are more similar to those reported by Bain and Brush (2005) in the eastern Piedmont of Maryland where they found that early (1820–1880) rates of 0.45–1.19 cm/yr were higher than more recent (1880–1963) rates of 0.08–0.46 cm/yr. Similarly, Jackson et al. (2005) reported an average of 1.6 m of historic sediment on floodplains in the Piedmont of Georgia since about 1820, which would produce a long-term rate of 0.87 cm/yr.

CONCLUSION

Historical records of Au mining in the Cid district of North Carolina suggest that the overall intensity of mining was considerably less than in the nearby Gold Hill district, but that some Hg may have been used to amalgamate Au. Our analysis shows that Hg contamination, albeit at relatively low levels (i.e., no samples exceeded the PEC for Hg), is evident in both the active channel sediments and historical floodplain deposits downstream from all mines in the district. We also found significant contamination by Cu, Pb, and Zn. This confirms historical accounts that, except for the intensive operations at Gold Hill, Au mining activities in North Carolina were more of a part-time activity that never fully replaced farming. Despite the low-level nature of the contamination, we were able to use Hg, Cu, Pb, and Zn concentrations in cores to estimate long-term sedimentation rates on several floodplains in the district. Sedimentation rates on active floodplain surfaces in each watershed range from 0.3–0.9 cm/yr, about two to three times less than rates at Gold Hill. These estimates further imply that the magnitude of landscape disruption by mining in the Cid district was less than that experienced in the Gold Hill district.

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