Differences in trace metal concentrations among fluvial morphologic units and implications for sampling

S. C. Ladd · W. A. Marcus · S. Cherry

Abstract This study examines the segregation of trace metals within and between fluvial morphologic units in sand-sized and finer bed sediments in a cobble bed stream. The types of fluvial morphologic units sampled are low gradient riffles, high gradient riffles, glides, eddy drop zones, lateral scour pools, attached bars, and detached bars. Three to nine samples were collected from ten of each type of morphologic unit. All 12 metals show significantly different concentrations between some morphologic units in sediments smaller than 2 mm. Eddy drop zones and attached bars consistently have the highest metal concentrations, while low gradient riffles, high gradient riffles, and glides typically have the lowest concentrations. Metals showing the greatest between-unit variability are Al, Cr, Fe, Cu, and Ti, followed by Co, Mn, and Pb, while Mg, Mn, V, and Zn display relatively few differences between units. Lateral and longitudinal variations of metals within units are not significant, and there was no consistent, predictable variation in metal concentrations with distance downstream. Results indicate that metal studies in other gravel- and cobble-bed streams should include a reconnaissance survey to determine variations between morphologic units, stratify sampling by morphologic unit, and analyze spatial autocorrelation to determine sample spacing.

Keywords Trace metal · Sediment · Pollution modeling · Hydraulics · Morphology · Classification · Sampling · Spatial autocorrelation

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Introduction

The contamination of fluvial and lacustrine sediments poses a direct threat to water quality, benthic fauna and flora, and organisms which feed in those environments (Marcus 1991). With the exception of metals in heavy minerals, however, few studies have examined the spatial distribution of trace metals in stream sediments at scales ranging from that of the stream unit (e.g., a riffle) to that of the stream reach (10 to 50 times the channel width). In particular, there has been little research on gravel- and cobble-bed streams which receive mining waste in mountain regions, even though biotic impacts in such systems can be severe (Moore and Luoma 1990; Moore and others 1991; Marcus and others 1995a; Nimmo and Willox 1996). Documenting and understanding metal concentrations in sediments over these scales in gravel- and cobble-bed streams is critical for: (1) developing sampling criteria for environmental and geochemical studies; (2) understanding local variations in environmental impacts; and (3) targeting portions of streams for remediation (Marcus 1989).

Previous studies at reach scales have shown that metal concentrations vary spatially as a function of grain size, sediment mixing, chemistry, and hydraulics. Most studies looking at variations in metal concentrations at scales of 1 to 500 m have focused on geochemically controlled changes immediately downstream of acid seeps, where rapid changes in pH, total dissolved solids, and dissolved oxygen content may occur (Förstner and Wittmann 1979; Salomons and Förstner 1984; Rampe and Runnells 1989). Under more typical stream conditions, however, studies suggest that local variability of metal concentrations in sand-sized and finer sediments is controlled more by hydraulics than the proximal geochemical systems in which the sediments are transported and deposited (Moriarty and others 1982; Marcus 1987, 1996; Graf and others 1991).

One reason why hydraulics control spatial variability of metals is that metal concentrations vary with sediment size. Fine grain sediments often have higher quantities of trace metals because of their greater surface area per unit volume and the cation exchange capacity of clays (Horowitz 1985). Moore and others (1989) have shown, however, that higher metal concentrations may occur in the coarser sediments, particularly in mined areas where mine waste and dominant sediment sources are often coarse grained and reflect the geochemical signature of the mined ore and waste rock. Alternatively, coarse-grained sediments in high energy systems can have longer residency times, allowing them to accumulate more metal from the surrounding waters due to oxide accumulation and subsequent metal scavenging (Whitney 1975; Chao and Theobold 1976; Tessier and others 1982).

The density of sediments can also play an important role when the metals are carried in heavy minerals. In general, heavy minerals accumulate at unit and reach scales due to variations in tractive force resulting from changes in particle roughness, bedforms, and channel geometry (Slingerland and Smith 1986).

In streams with a cobble component, local variability in metal concentrations has been documented between bars, sloughs, and main channel deposits in an ephemeral stream (Graf and others 1991), between riffle environments (Moriarty and others 1982), and between topographic features such as point bars, channel fills, ridges and swales in a floodplain (Wolfenden and Lewin 1977). Work by Fletcher and others (1987), Day and Fletcher (1989), and Marcus (1996), indicates that variations in stream energy are responsible for these local-scale differences in cobble streams. Despite the high average stream power in these streams, micro- to local-scale variations still create variations in tractive force which can selectively sort sediments by size and density.

A number of studies have examined the variability of metal levels within individual types of depositional units (e.g., within point bars) in cobble-bed streams. Moriarty and others (1982) found that metal concentrations within individual riffles in England did not vary significantly. Likewise, Day and Fletcher (1989) noted little difference in Au concentrations between bar-head gravel deposits in British Columbia, although concentrations in sands in lower energy bar-tail eddy pools in the same stream varied over a wide range. In contrast, Fletcher and others (1987) documented greater variations in Sn concentrations in Malaysia occurring in higher energy environments. Hakanson (1984) also noted increased variability in metal concentrations within transportational and erosional environments when compared to depositional settings. Regardless of which stream environments demonstrate the greatest within-unit variability, the geochemical exploration literature emphasizes the need to stratify sampling by stream environment in gravel- and cobble-bed systems to develop the most efficient sampling scheme (Hakanson 1984; Fletcher and others 1987; Day and Fletcher 1989; Paopongsawan and Fletcher 1993; Hughes and others 1995).

The above studies indicate that trace metals may segregate between fluvial morphologic units due to hydraulic sorting by size and density and due to the different residency time of sediments in different units. None of the studies, however, has systematically quantified the concentration variability within and between all units in a stream at local scales. The goal of this study is to determine the relation of channel morphology and trace metals in bed sediments within distances of 1 to 500 m in a cobble- and gravel-bed stream typical of many highland settings receiving waste discharge. Specifically, the study examines how concentrations of 12 metals in bed sediments vary within and between seven types of morphologic units. We conclude with recommendations for metal sampling strategies in similar stream environments.

Study area

The study area covers 500 m of Soda Butte Creek near Cooke City, Montana (Fig. 1). Hard rock mining for gold and silver above the study reach has left a legacy of mining-related metal sources such as tailings, adits, and old mill sites. In the study reach, Soda Butte Creek is a third order cobble- and gravel-bed stream with a laterally unstable wandering channel and a C3 to D3 Rosgen (1994) classification. The width of the active channel ranges from approximately 10 m where confined, to 150 m in braided sections. Bed sediment size varies with morphologic unit, ranging from loose deposits of clay, silt, and sand in eddy drop zones to well-armored gravel and cobble deposits throughout most of the active channel. Bed gradients range from 0 to 4% and vary with morphology. Detailed maps of channel morphology are presented in Ladd (1995). The study area corresponds to the "B Reach" of Marcus and others (1995b), who provide detailed descriptions of sediment size distributions of six cross sections within the study area. Preliminary findings on the local to watershed-wide metal distributions throughout Soda Butte Creek are described in Marcus and others (1996) while some of the ecological impacts of these metals are documented in Marcus and others (1995a) and Nimmo and Willox (1996).

The study area is (1) far enough from mine-related metal sources so that there is a relatively constant geochemical environment along the length of the reach and (2) approximately 150 m downstream from the nearest tributary, which avoids spatial variations in pH and metal concentrations due to mixing effects. Water hardness, alkal-

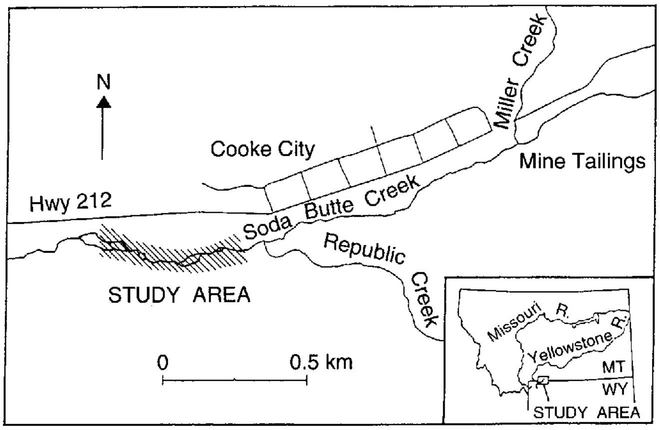

Fig. 1
Location of the study area

inity, pH, and dissolved oxygen content were relatively constant throughout the study reach during the period of sample collection from late July through August 1993. No discharges capable of moving bed sediments occurred during the sampling period.

Methods

Samples were collected within seven different types of fluvial bedform morphologies along the 500 m reach. The seven types of morphologic units were modified from systems proposed by Bisson and others (1982) and Church and Jones (1982). The Bisson and others (1982) classification scheme was chosen because it is widely used by the US Fish and Wildlife Service and the US Forest Service for habitat classification in streams and is simple to use in the field. The study area contained five Bisson-type morphologic units: lateral scour pools, eddy drop zones (also referred to as backwater pools), glides, low gradient riffles (< 1% slope), and high gradient riffles (1–4% slope). The remaining unit types from which samples were collected were two bar categories as defined by Church and Jones (1982): bank-attached bars and detached island bars.

The unit types are relatively easy to identify visually in the field at low flow based on shape, size, and water surface characteristics. Examples of morphologic units are illustrated in Fig. 2. Lateral scour pools occur where flow is diverted against a stable bank and typically have a cobble substrate. There is usually a transition from the tails of lateral scour pools into shallow, fast flowing, low turbulence glides with gravel and cobble beds. Flow in the lee of an obstruction often forms an eddy drop zone, which characteristically contains fine particles. Low gradient riffles have turbulent flow, sediments up to cobble size, gradients less than 1%, and are typically the largest units in Soda Butte Creek, extending for tens of meters. High gradient riffles usually occur at the tail of bars, contain emergent cobbles, and exhibit shallow and turbulent flow with bed gradients between 1 and 4%. Attached bars are active depositional zones (areas above water that lack vegetation) where at least one side of the unit is attached to the bank. Detached bars are islands of active alluvium with channel flow around them. Units are often very closely spaced, with all seven types sometimes occurring within 15 m of stream length (Fig. 3).

Sample locations were stratified by morphologic unit. Ten of each type of morphologic unit (e.g., ten glides, ten eddy drop zones, etc.) were sampled to determine variations in trace metals in bed sediments within units and between units. Three composite samples were obtained from seven of each type of unit (e.g., from seven of the ten sampled eddy drop zones) to determine the variability of trace metal concentrations in the downstream direction within each unit type and the variability between units. These composite samples in each unit were taken from a transect at the head, in the middle, and at the tail of the unit. Each composite consisted of a sediment scoop taken at the two sides of the unit and one scoop from the middle.

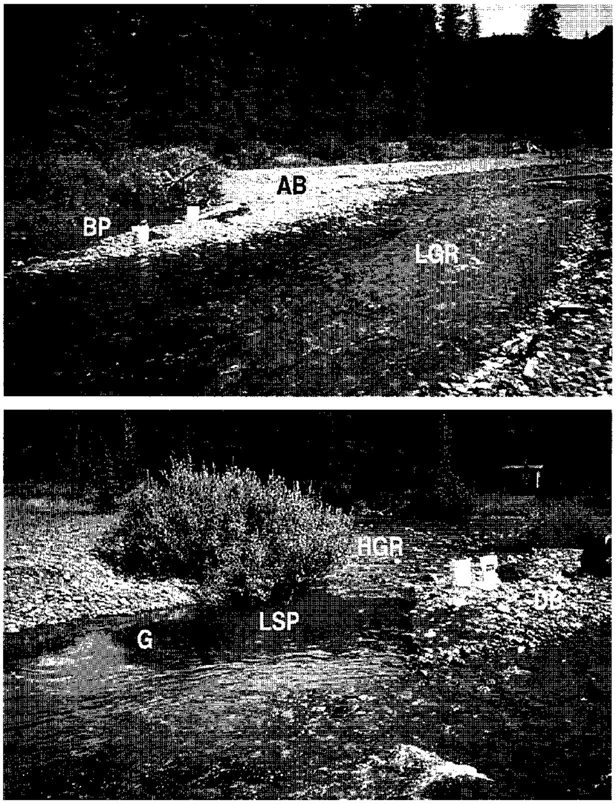

Fig. 2
Morphologic units in Soda Butte Creek. *AB* Attached bar; *BP* backwater pool; *DB* detached bar; *G* glide; *HGR* high gradient riffle; *LGR* low gradient riffle; *LSP* lateral scour pool

In addition, nine uncomposited samples were taken from within three of the ten unit types (e.g., from three of the ten sampled eddy drop zones), to determine the variability of trace metal concentrations perpendicular to the stream flow (laterally) as well as longitudinally within each unit. The locations of sample sites in each unit (e.g., in each glide) were chosen so that equal spacing was maintained between the three transects and between sample points within each transect. The average and range of distances between sample transects within each type of unit are shown in Table 1.

Sediment was sampled through a 20 l bucket with the bottom removed. After removing the surface armor of cobbles and gravels, approximately 375 ml of sand-sized and smaller sediments were removed at each sample site from the top 5 to 10 cm of the bed. Analysis of suspended sediment concentrations within the bucket water column during ten sample collections indicated that suspended sediment loss was not likely to have changed overall metal concentrations in the bulk sample by more than 0.68% (Ladd 1995).

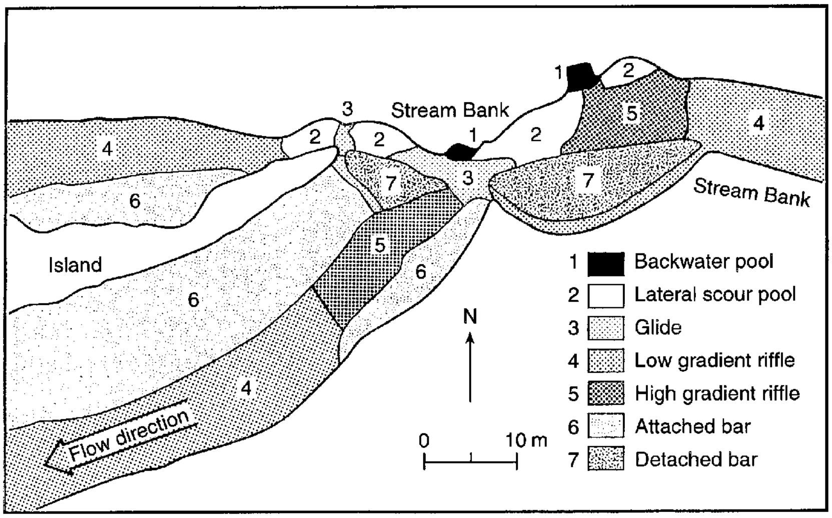

Fig. 3
Spatial variability in morphologic units. Note the large number of different units located in a relatively small stream area

Table 1
Sample spacing between sample transects in Soda Butte Creek, Montana

	Longitudinal distance (m) between sample transects in each type of unit		Lateral distance (m) between sample transects in each type of unit	
	Average	Range	Average	Range
Low gradient riffle	12.9	4.0–35.0	2.1	0.9–4.1
Attached bar	6.5	1.2–17.7	1.2	0.4–3.2
High gradient riffle	5.0	2.3–10.5	1.7	0.6–3.2
Detached bar	4.3	1.2–10.0	1.3	0.6–3.2
Lateral scour pool	3.4	1.3–7.2	0.4	0.3–0.6
Glide	2.4	1.0–5.4	1.4	0.7–2.3
Eddy drop zone	1.4	0.6–2.2	1.0	0.5–1.6
	$n=19$	$n=19$	$n=16$	$n=16$

Samples were dried at 35 °C and then dry sieved through a stainless steel screen. The 2 mm (very coarse sand) and finer fractions were retained for metal analysis. Samples were not ground in order to focus on the metals which are potentially mobile in the environment rather than on the whole rock metal content. A 1 g subsample was taken from each sample for inductively coupled plasma (ICP) analysis. A 25 ml 3:1 solution of nitric and hydrochloric acids (aqua regia acid) at 150 °C was used to prepare samples for ICP analysis. Five percent of all samples were reference standards. Instrument drift for standards could not vary by more than ±10%. One of every 40 samples was a blank and one of every 40 samples was a duplicate.

Data

Sediment samples (336) from 70 morphologic units were collected. Al, Co, Cr, Cu, Fe, Mg, Mn, Ni, Pb, Ti, V, and Zn in the 2 mm and finer fractions all had concentrations which were within the detection limits of the ICP analysis for all samples. Metal data for these 12 metals for each unit type are summarized in Fig. 4.

Statistical analysis

The following analysis evaluates whether there are significant differences in concentrations between different types of units (e.g., between lateral scour pools and attached bars) and within individual unit types (e.g., between the upstream and downstream ends of high gradient riffles). A significance level of 0.05 was used for all statistical tests.

The statistical analysis section is started with a section on descriptive statistics, which provides a broad overview of concentrations in different morphologic units. This is followed by an analysis of variance (ANOVA) to assess whether concentration differences among units are statistically significant. ANOVA is available on almost all sta-

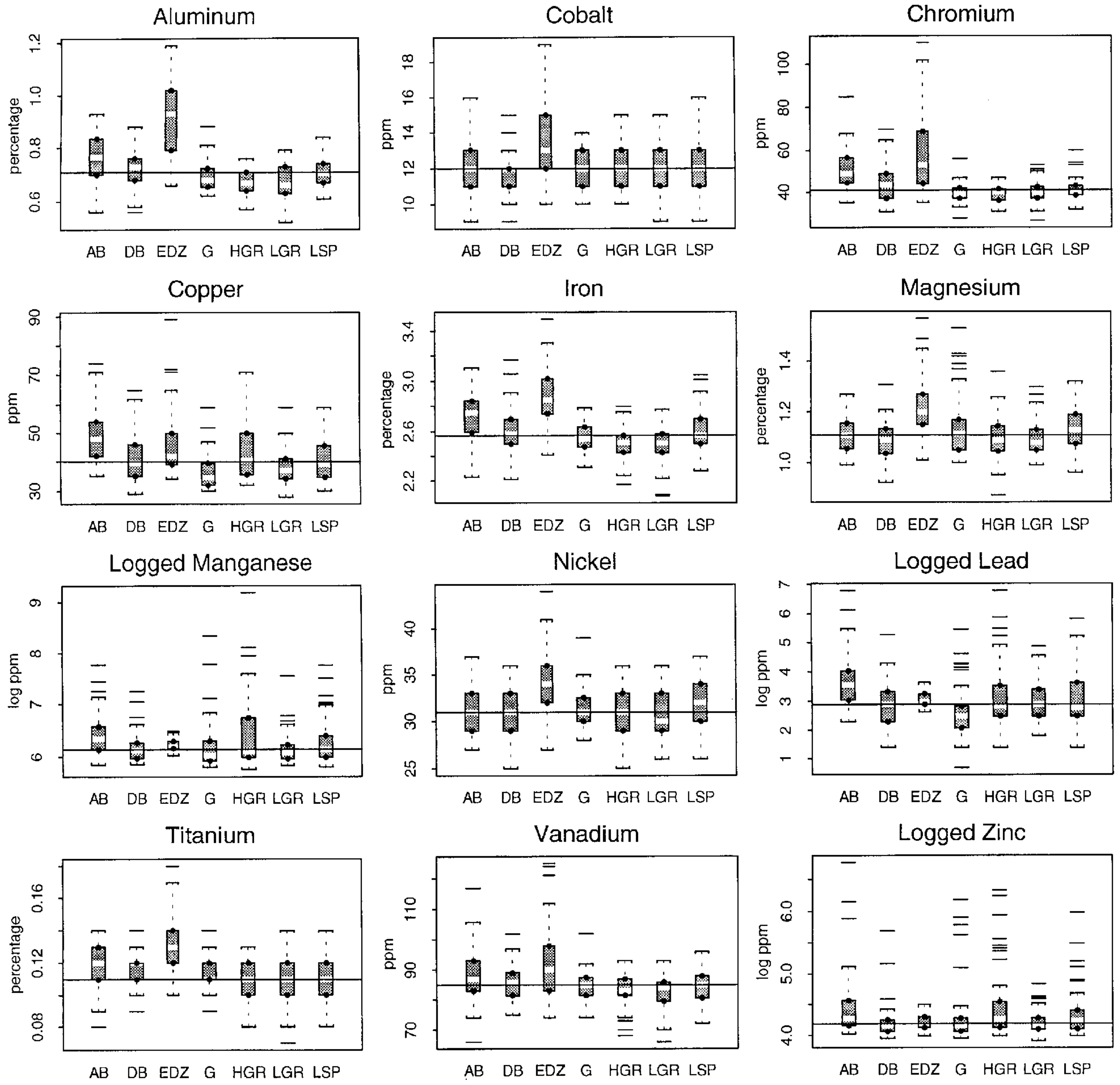

Fig. 4

Box plots of metal concentrations in different morphologic units. *AB* Attached bar; *DB* detached bar; *EDZ* eddy drop zone; *G* glide; *HGR* high gradient riffle; *LGR* low gradient riffle; *LSP* lateral scour pool. *Solid black line* indicates median concentration for all units combined; *White line* Median concentration for each unit; *grey* intermediate quartile ranges of the metals; *brackets* 1.5 times the quartile range or the full range of data, whichever is smaller; *horizontal lines* outliers beyond 1.5 times the quartile range

tistical software packages and is probably represents the level of statistical analysis which most environmental managers can undertake. However, ANOVA only provides a rough guide to whether metal populations are truly different, because some of the assumptions required for its use are violated by our data. We thus conclude with a more complex analysis where all statistical assumptions are met.

The role of channel morphology

Description of variations among units

Concentration variations within and between morphologic units are shown in Tables 2 and 3. The clustering of high or low concentrations of Cu, Fe, Pb, and Zn in certain units is demonstrated in Table 2, which shows the percentage of concentration measurements for each unit type that fall within a certain quartile. For example, 26 of the 76 sites that make up the upper quartile of iron con-