Geomorphological Context of Metal-Laden Sediments in the Animas River Floodplain, Colorado

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ABSTRACT

The watershed of the upper Animas River in the San Juan Mountains of Colorado was the site of extensive mining and ore milling during the late 19th and early 20th centuries. Using geologic mapping, stratigraphic and sedimentological studies of floodplain sediments, geochronology, historical records, and geochemical analysis of sediments, we conclude the following. Prior to mining, the river valley below the town and ore mill site of Eureka was composed of small, multi-thread, gravel bedded channels. These were located within a silty floodplain consisting of willow thickets and possibly intermittent and localized beaver ponds. A radical change in the stream and floodplain environment started sometime around the turn of the century and concluded with aggradation and burial of older sediments with sheets of gravel. This was caused by ore milling, not mining or other activities. Mills in and near Eureka supplied huge quantities of tailings to the river, at rates 50 to 4,700 times greater than the natural (pre-mining) production of sediment from hillslopes. Floodplain sediments have naturally high zinc concentrations of about 1000 parts per million, but ore milling resulted in an increase of zinc concentrations by as much as an order of magnitude. Using vanadium as a lithologic tracer for sediment derived from natural erosion of the watershed, we estimate that the fine fraction of streambed and floodplain sediments deposited after 1900 A.D. contain, in general, two-thirds tailings and one-third natural sediments.

INTRODUCTION

The geomorphological context, depositional setting, and age of sediments used for chemical analysis and delineation of metals added to the environment by historical mining activities, can add insight into the cause and the disposition of those contaminants. Geologic mapping, stratigraphic and sedimentological studies, geochronology, and historical records were used to delineate the depositional timing and stratigraphic distribution of metal-laden sediments in the upper Animas River floodplain. This study illustrates the utility of multidisciplinary approaches in environmental studies, by establishing the pre-mining level of metals in upper Animas River streambed and floodplain sediments, and by demonstrating that the increase in concentration of certain metals in streambed and floodplain sediments coincided with the onset of ore milling activities upstream.

Beginning in the 1870's, the San Juan Mountains of southwestern Colorado was the site of extensive mining and milling of ores containing gold, silver, lead, copper, and zinc (Bird, 1986). The mine and mill sites numbered in the hundreds, but most were short lived. Early mills were constructed exclusively along streams, in part so that tailings would be dispersed downstream, rather than accumulate at the mill sites. By 1920, ore processing mills had become centralized and slurries of mill tailings were discharged or impounded on the floodplains of major streams. During major floods, the mill tailings were transported downstream, dispersing ore-related metals and contaminating downstream floodplains. The present location and extent of tailings in floodplain sediments is largely undocumented. Furthermore, the concentrations of metals in pre-mining streambed and floodplain sediments is unknown. The objective of this study is to address the pre-mining environment of the now braided section of the upper Animas River, determine the pre-mining concentrations of ore-related metals, and provide a chronology that can be tied to historical records of milling activity at Eureka, Colorado.

A trench was excavated across the floodplain of the upper Animas River in order to expose sediments, stratigraphic relationships, and datable material. The site is located upstream of Silverton, and is 1.4 km downstream of the now-defunct mill and town-site of Eureka. This is a subalpine setting at altitude of 2,970 m (meters). The site is identified as locality 3 on the regional location map of Church and others (their fig. 1, 1999). The floodplain surface consists of multiple braided channels, gravel bars nearly devoid of vegetation, and stream-deposited tailings. The trench spanned 360 m, nearly the full width of the floodplain, and averaged 2.0 m in depth.

METHODS

The geomorphology of the site was studied by mapping geomorphic surfaces, investigating the stratigraphy exposed in the trench, and determining the numerical age, or constraining age, of the various sedimentary deposits. The purpose of the stratigraphic investigation was to decipher the environment of deposition of the sediments, to determine whether any sediments were mill tailings, and to establish the relative, or stratigraphic, ages of the deposits. This involved observation of cross-cutting stratigraphic relationships, sedimentological textures and structures, sedimentary provenance, and biological indicators of environment or age. Sedimentary contacts and structures, sample locations and other information, were documented on a log of the trench wall (unpub. data, 1998).

The numerical age of sedimentary deposits was determined using a variety of tools that provide either an age, or a maximum- or minimum-age constraint. Aerial photographs, taken on known dates, were inspected for the presence or absence of surficial deposits and other identifiable features. Numerous historical artifacts were discovered in the trench wall, constraining the age of the host deposits to be post-1870. These artifacts include iron objects: cans, pots, barrel hoops, and a stove leg; cloth fabric; porcelain; and a brick. A post-1870 age was also established for deposits that consisted of early mining stamp-mill tailings or were stratigraphically above tailings deposits. The annual growth rings of willow stems were used to constrain the age of deposits in which the plants were rooted, and were used to estimate the age of subsequent deposits that partially buried the willow plants (Scott and others, 1997; Sigafoos, 1964). Radiocarbon ages were obtained for twigs and peat found in sedimentary deposits.

Samples for chemical analysis were extracted from the trench wall, or obtained from cores of tailings and silt beds. The trench wall samples were generally about one liter in volume. Four 5 cm (centimeter)-diameter cores, about 1-m long, were taken along the trench. The cores were subsequently divided into 4 to 12 subsamples, with typical volumes of 50 cm^3 (cubic centimeters), based on stratigraphy (that is, visual differences of mineralogy or sedimentology).

Sample preparation and geochemical analysis follows the methods used by Church and others (1997) in their study of the geochemistry of modern streambed sediments of the upper Animas River and its tributaries. All samples containing gravel were passed through a stainless steel sieve with 2 mm (millimeter) mesh opening, and the gravel clasts were discarded. All samples were air dried, and sieved to -100 mesh (< 0.15mm), and then crushed to -150 mesh (< 0.1mm), except for the early stamp-mill tailings, which were crushed to -150 mesh without sieving. The chemistry was determined for very fine sand, silt, and clay-sized particles in the samples of silt-beds, fine-grained tailings, and sandy gravel. For the stamp-mill tailings samples only, the chemistry of the coarse sand and finer particles were determined. The analytical results are therefore representative of the entire samples of silt-bed and tailings deposits, but representative of only the fine-fraction (< 0.15mm) of the sandy gravel samples. The fine-grained particles, in the sandy gravel samples, generally occupied <5% of the original sample mass.

After grinding, all samples were digested using a mixed-acid procedure (Briggs, 1996), by which near complete dissolution of the samples was accomplished. This procedure is very effective in dissolving most minerals, including silicates, oxides and sulfides. Some refractory minerals such as zircon, chromite, and tin oxides are only partially attacked; however, elements contained in these minerals were not of concern in this study. The resulting solutions were analyzed by inductively coupled plasma-atomic absorption emission spectroscopy for major elements and trace elements. We discuss here results for zinc and vanadium. To monitor the quality of analyses, laboratory duplicates were analyzed to assess precision, and three standard reference materials were analyzed with the sample sets to assess analytical accuracy. The reference materials were NIST-2704, NIST-2709, and NIST-2711, available from the National Institute of Standards and Technology (NIST, 1993a, 1993b, and 1993c).

RESULTS

Production of ore-mill tailings

The history of mining and ore milling (fig. 1) upstream of the trench site is presented in order to identify the sources and ages of metal-laden sediments exposed in the trench. The history focuses on a succession of mills at Eureka (1.4 km upstream of the trench), various mines and mills near the Animas Forks town-site, which is also on the Animas River (8 km upstream of the trench), the Midway Mill about 3 km up Eureka Gulch from its confluence with the Animas River at the Eureka town-site, and the Sunnyside Mine on the shores of Lake Emma and its early mill (in upper Eureka Gulch, about 5.5 km upstream from the Eureka town site).

The first prospectors explored the area in 1860 and found a small amount of gold near the eventual site of Eureka, but the Civil War brought those types expeditions to a halt (Bird, 1986). In 1871 expeditions resumed and the prospectors learned that placer mining would not be viable, but that money could be made mining hard rock. Mining did not begin in earnest until after the September 13, 1873, Brunot Treaty which ceded land from the Ute Indian tribe. Through the 1870's mining produced valuable metals, but the quantity of ore (hand sorted and "high-graded" by miners and shipped from the area on mules and burros for processing) was relatively small. Mines around Animas Forks, for example, "were worked in the 1870's and produced 800 tons of ore" (Marshall, 1996, p. 140). During the 1880's and 1890's mining (and eventually ore milling) occurred at a limited scale and was intermittently disrupted by mechanical failures, natural disasters, and economic setbacks. In 1888 the first mill was constructed close to the Sunnyside Mine (a "ten-stamp" mill), and late in 1889 the Midway Mill began operation and processed 15 tons per day (Bird, 1986). Stamps were added to the Midway Mill in 1897, increasing capacity to 50 tons per day, and the first mill in Eureka, designed for a capacity of 125 tons per day, was constructed in 1899 and began production in 1900 (Marshall, 1996).

These stamp mills were generally in full production from 1900 to 1918, but were inefficient. A "stamp" was a piston device used to crush ore to sand-size, and economical minerals were then concentrated using various means, generally mechanical, for railroad shipment to smelters. The remaining material was discharged from a mill's tail-race into the Animas River or its tributaries, and these tailings contained metals. The Eureka Mill, for example, recovered less than 50 percent of the metals contained in lead-zinc ores (Bird, 1986, p. 68). Late in 1904 the Silverton Northern Railroad began service to the town of Animas Forks and the new Gold Prince Mill located there. The Gold Prince Mill was huge, with a reported capacity of 500 tons per day (Marshall, 1996), but production from the mill (and others in the area) was probably small. It was dismantled in 1910, and railroad service to Animas Forks was abandoned in 1916 (Sloan and Skowronski, 1975). Uniquely, the Sunnyside Mine remained profitable, because its ores were rich in gold, and in 1910 the Eureka Mill was processing 3,500 tons of ore per month (Bird, 1986, p. 114). In 1912 an electrostatic zinc recovery plant was added to the Eureka Mill (presumably reducing zinc concentrations in the mill tailings) and that and rising zinc prices probably saved that mine (unlike the others) during World War I.

A new era began in 1918. A new mill was completed in Eureka, capable of processing up to 600 tons of ore per day using a revolutionary selective flotation process that increased mill efficiency and profitability (Bird, 1986). Ore crushing techniques were also significantly improved at this time, resulting in fine-grained tailings composed of silt-sized and finer (<300 mesh) particles. The old stamp mills were abandoned. Full scale production was hampered, however, because of various disasters, until the end of 1919, and then the mine was forced to close late in 1920 because metal prices plunged. The boom years began when the mine reopened in the fall of 1921. The mine was producing 16,000 tons of ore per month by 1923, 20,000 tons per month by 1925, and broke all records by producing 1,100 tons of ore per day by 1929 (Bird, 1986). After the October stock market crash, however, the Sunnyside Mine and Eureka Mill struggled and then closed in September 1930. The mine was reopened again in 1937, faltered, and closed in August 1939. At the time of closing, a total of 2,500,000 tons of ore had been mined and milled, producing $50,000,000 in metals, and Eureka was officially a ghost town (Bird, 1986).

Figure 1 illustrates the rates at which ore was milled, in U.S. short tons per day. About 80 to 90% of the processed ore was released as tailings (King and Allsman, 1950). Using the 80% value and the ore processing rates on figure 1, mill tailings production rates were calculated and converted to metric tonnes. Most coarse-grained stamp mill tailings were produced between 1900 and 1918, at rates in excess of 35,000 tonnes per year. Most fine-grained tailings were produced after 1921 and before 1930, at rates between 150,000 and 330,000 tonnes per year.

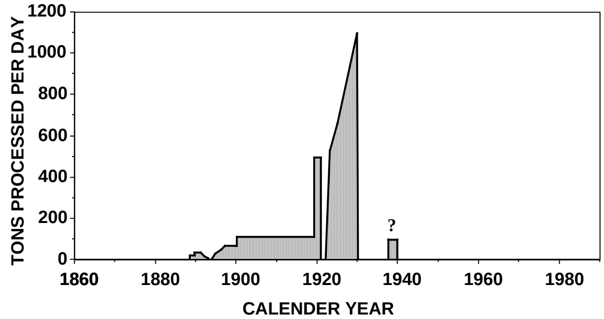

Figure 1. Combined ore processing rates for the succession of mills in the town of Eureka, Colorado, and in Eureka Gulch. These rates (from Bird, 1986; Marshall, 1996; and Sloan and Skowronski, 1975) were quoted in “tons”, which presumably means U.S. short tons. One short ton equals 1.016 metric tonnes. Between 80 to 90% of the processed ore was discharged from the mills as tailings (King and Allsman, 1950).

Other sources of sediment

The rates of sediment supply from other sources are estimated for comparison with that from ore milling. Known rates of hillslope sediment yield span 6 orders of magnitude, from 0.004 to 500 tonnes/hectare/year. These two numbers are for primeval forests and for some croplands and construction sites, respectively (Dunne and Leopold, 1978). The prehistorical sediment production rates for the upper Animas River setting were probably at the low end of that spectrum, around 0.01 or perhaps 0.1 tonnes/hectare/year, resulting in total yield from the 73.6 km^2 watershed of 74 to 740 tonnes per year, respectively.

Logging probably did not increase sediment yields significantly because only 12% of the watershed is forested, and only a fraction of that was logged. The area was grazed, and grazing can increase sediment yields by an order of magnitude (Dunne and Leopold, 1978), but only about half of the upper Animas watershed is soil mantled and thus susceptible to increased erosion by grazing. Grazing and to a lesser extent logging, therefore, may have increased the watershed sediment yield by hundreds to a few thousand tonnes per year.

Erosion of mine-waste dumps also supplied sediment to streams. There are 24 mine shafts, 209 mine portals, and 679 prospect pits in the watershed above the trench site, based on the mining symbols on the USGS topographic maps. Each of these excavations has a pile of waste rock, and each waste dump contains about 200 tonnes of material covering an area of about 50 m^2, on average (T. Nash, oral commun., 1999). Together, the waste dumps cover an area of approximately 4.5 hectares. An erosion rate of 100 tonnes/hectare/year is typical for disturbed land in general (Dunne and Leopold, 1978). If this is appropriate for mine dumps, all of the dumps in the watershed lost 450 tonnes of sediment per year, but only a fraction of the sediment mobilized from dumps reached streams because most mine sites are located high on hillslopes many kilometers from streams.

Geomorphological findings

Sediments exposed in the trench generally consist of sandy gravel deposits (83%), silt beds (12.6%), lenses and tabular beds of sand-sized tailings (1.2%), and tabular beds of fine-grained tailings (3.2%). The percentages refer to the area of each deposit type relative to the total 607 m^2 area of the trench wall. The trench was excavated perpendicular to stream flow. The base of the section consists of massive sandy gravel locally containing (1) discontinuous parallel bedding usually inclined <5°, (2) medium, curved, parallel, trough cross-bedding, and (3) 16 thin-to-medium, lenticular (two are tabular) beds of brown sandy-silt <3 m in length.

Eight thick to very-thick beds of brown sandy silt are found in the middle of the section. The silt beds range in length from 4 to 25 m and span •30% of the trench length. The bases of the silt beds are generally in planar-horizontal contact with underlying gravel, but lenticular- or wedge-shaped silts also interfinger with underlying gravel. Twigs and peat found near the base of the silt beds have ages of 1,080 ±120 and 2,130 ±145 ^{14}C years before present. At one location, a facies of gravel interfingers with coarse-grained tailings which in turn interfingers with the base of a thick silt bed. From this we infer that the silts were deposited in an impounded channel and are historical (post-1900 A.D.) in age. The silt beds contain (1) lenses of gravel, (2) a few lenses of peat (up to 5 cm thick and <3 m long), (3) 14 peat lamina (1 cm thick and 1 to 10 m long), (4) leaves and root casts possibly left by grasses, and (5) abundant twigs (presumably willow), some of which are in growth position. One twig was obviously chewed by a large mammal, possibly a beaver. Aside from those features, the silt beds appear massive. Close inspection, however, indicates that the silts beds also contain very thin lenses of fine sand, irregular shaped bands of climbing ripples composed of coarse silt, and 10-cm-deep indentation markings left by large mammal hooves. The silt beds are either overlain conformably, or are truncated by wavy or irregular erosional surfaces. Twigs and peat found near the top of silt beds yielded two “modern” C^{14} ages, which means they are <300 years in age.

Channel-fill deposits truncate the lateral extent of thick silt beds at several locations. These channel-fill deposits consist of sandy gravel that contain (1) discontinuous parallel bedding, (2) medium, curved, parallel, trough cross-bedding, (3) and thin, lenticular or irregular-shaped deposits of coarse sand. Nine of the sand lenses are dominated by very angular grains of ore body minerals (sphalerite, rhodenite, and pyrite), and two lenses contain historical iron objects. We infer that these are deposits of stamp-mill tailings. The upper meter of the section consists of sheets of sandy gravel that are either horizontally bedded or trough cross-bedded. These gravels contain lenses and two beds (3 to 11 m long) of stamp-mill tailings, and historical objects. The following ages are based on growth rings of willows buried by the gravels (M. Scott, USGS, BRD, written commun., 1999). The sheet gravels were deposited during floods that occurred before 1915 A.D. and about 1920 A.D., and the depositional age of the top of these sheet gravels was determined to be 1930 A.D. (± 3 years). This depositional surface extends over 45% of the length of the trench, although it is locally covered by beds of fine-grained tailings. Elsewhere it has been remobilized by flow within braided channels.

The beds of fine-grained tailings are generally massive and are thin to medium in thickness. Willow growth rings indicate the tailings beds were deposited by floods that occurred about 1940 A.D. and about 1970 A.D. (M. Scott, written commun., 1999).

Geochemical results

The stratigraphic investigation provided the basis for ranking the deposits by relative age (fig. 2A and 2B), and allowed us to establish the trends in element-concentrations in the streambed and floodplain sediments. The C^{14} ages allowed identification of those sediments which were definitely deposited before the mining era (fig. 2C). The age constraints provided by the presence of tailings and historical artifacts, and the growth rings of willows, allowed identification of those sediments which were definitely deposited after milling began (fig. 2C). The geochemical data are presented using symbols for 4 deposit types, but in general the sedimentary deposit type does not influence concentrations.

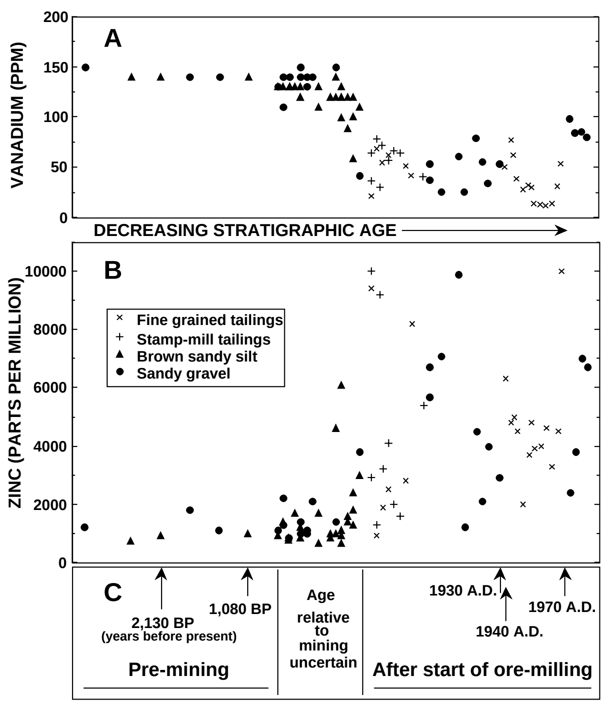

Figure 2. The concentrations of (A) vanadium and (B) zinc in the fine-fraction of sediments of various types, plotted against stratigraphic (relative) age. Numerical ages, based on radiocarbon and tree-ring analysis, are tied to the relative age scale in fig. 2C, and the presence of tailings beds and cultural artifacts identify sediments deposited after the onset of ore milling. All samples were obtained from the trench excavated into Animas River floodplain 1.4 km downstream of the town-site of Eureka, Colorado.

The concentrations of vanadium in sediments (fig. 2A) deposited prior to mining average 140 ppm (parts per million), which is near the 160 ppm crustal abundance of vanadium (Emsley, 1991), and are typical of bedrock in the study area. The concentrations of vanadium in historical (post-1900) deposits average 50 ppm. The vanadium concentrations in some of the fine-grained tailings samples are close to 20 ppm. Thus, the relative loading of natural sediments and mill tailings can be calculated from the dilution of vanaduim in historical sediments.

The concentrations of zinc in sediments (fig. 2B) deposited prior to the mining era are uniform and close to 1000 ppm, which is an order of magnitude greater than the 75 ppm crustal abundance of zinc (Emsley, 1991). Compared to this pre-mining background, the concentrations of zinc in most (38 out of 46 samples) of the sediments known to have been deposited after mining began are elevated by as much as ten times. The zinc concentration data do not show patterns of association with sedimentary deposit types.

DISCUSSION AND CONCLUSIONS

We conclude that most metal-laden sediment at the trench site originated from ore-processing mills in and near Eureka. Most of the coarse-grained stamp mill tailings were produced between 1900 and 1918, at rates in excess of 35,000 tonnes per year. That supply rate is 50 to 500 times the natural (pre-mining) production of sediment by erosion from hillslopes in the watershed which is estimated to have been in the range of 70-700 tonnes per year. Most fine-grained tailings were produced after 1921 and before 1930, at rates between 150,000 and 330,000 tonnes per year. Those rates are 200 to 4,700 times greater than the natural production rate of sediment eroded from hillslopes. Accelerated erosion caused by logging and grazing and erosion of mine waste dumps may have contributed a few thousand tonnes of sediment a year, but those sediments contain much lower concentrations of zinc, for example, compared to tailings as discussed below.

The following late-Holocene geological history of the Animas River floodplain is deduced from the results of the trench study discussed above. Prior to 2,000 years ago the fluvial system was dominated by fully braided streams with little silt-bed deposition, or at least little silt-bed preservation. Later, the valley bottom became composed of small, multi-thread, gravel bedded channels coexisting with floodplains consisting of willow carrs and possibly intermittent and localized beaver ponds. The willow thickets (and beaver ponds if and where present) were the terrestrial riparian habitat alongside the multi-thread streams, and were the depositional sites of silt beds. This stream and floodplain condition persisted for some 2,000 years, including an unknown number of decades after mining began in the 1870's.

A radical change in the stream and floodplain environment occurred sometime around the turn of the century, apparently starting with channel incision and widening, followed by aggradation and burial of older sediments with sheets of gravel. Because the aggradational gravel deposits contain lenses of coarse stamp-mill tailings, we interpret that most or all of the gravel aggradation occurred coincident with the major production period of mill tailings, after 1900. Gravel aggradation included deposition during numerous floods including one around 1930, after which gravel aggregation ceased. The Eureka Mill also closed in 1930. We infer that the aggradational episode was caused by the unnatural supply of huge quantities of tailings to the Animas River. Since 1930, the stream has been fully braided with no deposition of silt beds, and the gravel bars are nearly devoid of plant life. During floods in recent decades, however, fine-grained tailings remobilized from near the Eureka mill site were deposited on the braided plain and on remnant willow-covered floodplains downstream of the trench site.

The stratigraphic investigation provided the basis for ranking the deposits by relative age (fig. 2), allowing us to establish trends in element-concentrations in the streambed and floodplain sediments. The C^{14} ages allowed identification of those sediments which were definitely deposited before the mining era. The age constraints provided by the presence of tailings and historical artifacts, and willows growth rings, allowed identification of those sediments which were definitely deposited after ore-milling began. Using this information together, we identify the effect of ore milling on sediment chemistry (fig. 2).

The trend in zinc concentration shows a dramatic increase, by as much as an order of magnitude (fig. 2B). This increase occurred both in sediments deposited in streambeds and bars, and in sediments deposited on brush-covered floodplains. The concentrations of zinc in sediments known to have been deposited prior to the mining era are uniform and close to 1000 ppm. The range is from 750 to 1800 ppm. These sediments were the result of natural erosion of hillslopes in the watershed. The concentrations of zinc are also close to 1000 ppm in most of the samples that have depositional-ages which are uncertain relative to the beginning of mining and milling. Zinc concentrations for all but 5 of the youngest samples range between 650 and 2200 ppm. The concentrations of zinc are elevated, however, in most of the sediments known to have been deposited after mining began, and more specifically after mill-processing of ores began in earnest. Zinc concentrations for all but 8 of the 41 samples exceed 2200 ppm. We infer, therefore, that the increase in zinc concentrations in streambed and floodplain sediments was caused by the release of huge quantities of tailings from ore mills.

The trend in vanadium concentration is opposite to that for zinc (fig. 2A). The vanadium concentrations in pre-mining sediments are similar to that for typical bedrock in the area. They are also, in general, about three times higher than the concentrations in historical deposits. The vanadium concentrations in some of the fine-grained tailings samples are close to 20 ppm, and thus may represent pure tailings undiluted by natural sediment. Mining did not cause an increase in the release of vanadium to the environment, rather it diluted the natural vanadium concentration with mill tailings. We conclude that vanadium can be used as a lithologic tracer for sediment derived from natural erosion of the watershed. In this case, we conclude that the fine-grained fraction of historical sediments at the trench site are, in general, composed of two-thirds mill tailings and one-third natural sediments unrelated to mining or milling.

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