Post-mine metal transport and attenuation in the Keno Hill mining district, central Yukon, Canada

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Abstract The Keno Hill mining district in central Yukon was the second largest silver producer in Canada with mines operating from 1913 to 1989 on more than 65 vein silver deposits. The seven and a half decades of mining activities have generated large volumes of mine waste disposed on the land surface, resulting in elevated metal contents in numerous small drainages. To assess the extent of metal mobilization, old mine workings and the associated mine waste were examined and the water courses draining to a major river valley sampled. The results of field observations and an array of water and sediment analyses led to three major conclusions. 1. Acid mine drainage is not widespread because of galvanic protection of pyrite from oxidative dissolution and neutralization by carbonates in the country rock. 2. Mechanisms operative to limit aqueous metal transport in small streams in the district include cryogenic precipitation, coprecipitation and sorption. 3. The near-surface concentration of metals limits the options of waste disposal in future mining developments due to potential metal-leaching problems.

Key words Environmental assessment · Metal transport · Attenuation mechanisms · Remobilization: zinc, cadmium

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Introduction

The Keno Hill mining district is located in central Yukon, 354 km by road north of Whitehorse, the capital city (Fig. 1, inset). More than 65 vein silver ore deposits and prospects hosted by Upper Paleozoic quartzite and schist have been identified in a belt about 8 km wide and 22 km long. With a total silver production in excess of 6.4 million kg since 1913 (Watson 1986), the mining district was the second largest silver producer in Canada (Franzen 1986). Argentiferous galena and silver-containing sulphosalts including freibergite are the primary ore minerals. These minerals, frequently associated with sphalerite, pyrite and manganiferous siderite, occur in quartz veins within *en echelon* faults related to Mesozoic brittle deformation of the area.

Due to the high costs of ore transportation from the area, most mining operations in the early days selected the visibly richest ore (commonly hand-sorted) for shipment and large amounts of variably mineralized waste rock were disposed near portals and open pits. The waste rock was often used as riprap and in road construction. Consequently, an area in excess of 17 km^2 contains local concentrations of exposed mineralized rocks. The affected area remains sparsely covered by vegetation because of the near-treeline setting and harsh climate.

Although mining has ceased since 1989, there remains active exploration in the area and public concern about environmental degradation resulting from high metal discharge and the possibility of acidic drainage from some of the abandoned mine workings. To aid evaluating environmental impacts of past mining activities, this paper examines water-rock/soil interactions occurring in the area. The major metal transport and attenuation mechanisms are identified and the implications to future mining development are briefly discussed.

Physiography and geology

Most mining in the district took place in the north-facing, vegetated slopes of Galena Hill (1444 m) and Keno Hill (1849 m) above the 10-km-wide valley of the South McQuesten River (average elevation 760 m). The hills are

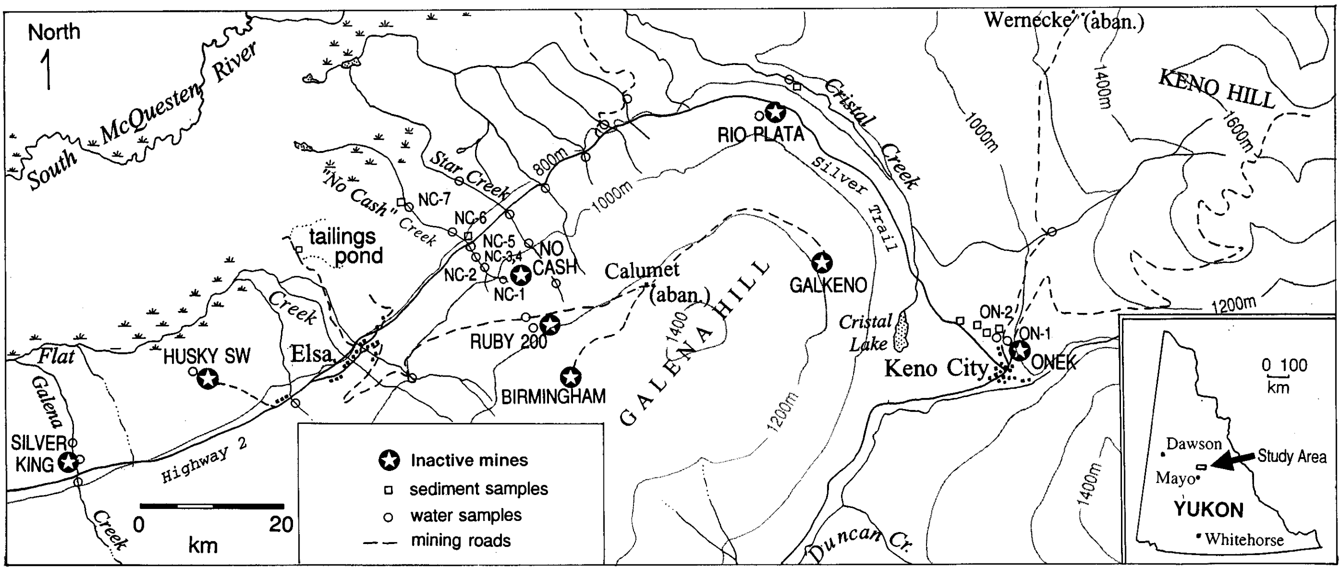

Fig. 1
Site and sample location map, Keno Hill mining district, Yukon

separated by Cristal Creek, with Keno City (elevation 945 m) at its head (Fig. 1). Both hills and major drainage have been modified by two glaciations within the last 120,000 years (Hughes 1982). The earlier Reid Glaciation covered Galena Hill and reached about 1600 m elevation on Keno Hill. During the later, less extensive McConnell Glaciation an ice lobe occupied the South McQuesten valley and kame terraces are evident at 1300 m on the north side of Galena Hill. The ice lobe also filled the Cristal Creek valley.

Water courses sampled in this study (Fig. 1) flow northward down slopes underlain by discontinuous permafrost. The streams are intermittent or dry in August-September and frozen from October through April. Even under peak flow conditions during spring runoff, some of these streams do not sustain surface drainage down to the McQuesten River valley but terminate in local gravel sumps at the base of the slopes. On the slopes, stream bottoms generally consist of pebble- to boulder-sized rock fragments from bedrock as well as lag from overlying glacial deposits. The hillsides are mantled by a hummocky veneer of bouldery sand and clay which has been locally modified by solifluction since glacial melting. Black spruce and mountain fir are scattered in the thick mat of sphagnum and labrador tea bushes, and dense slide alder choke stream gullies. Higher elevations are better drained, dwarf birch and scrub willow predominate above the tree line. The South McQuesten valley is underlain by boulder clay and covered by ponds, swamps and spruce forest. The Cristal Creek valley and kame terraces contain considerable sand hosting aspen and dwarf birch thickets in addition to spruce forests.

The bedrock geology of the region is described by McTaggart (1960), Boyle (1965) and Roots and Murphy (1992). The three principal rock units present in the study area are: (i) Devonian-Carboniferous Earn Group metasedimentary and metavolcanic rocks; (ii) Early Carboniferous Keno Hill Quartzite; and (iii) meta-diorite of Late Triassic age. The Earn Group includes carbonaceous phyllite, siliceous phyllite and less common porphyritic phyllitic felsic metavolcanic rocks. The overlying Keno Hill Quartzite consists of dark gray orthoquartzite with lenses of chloritic phyllite and rare limestone pods. Meta-diorite plugs and lenses abundantly intrude both units. The meta-diorite is a dense, dark-green and fine-grained rock that forms knobs and cliffs. Carbonate veinlets are present in all three rock units and some phyllite contains locally visible interstitial calcite.

Cretaceous regional metamorphism resulted in ductile deformation of the Keno Hill Quartzite and Earn Group rocks, while the original diorite intrusions were stretched into elliptical bodies. Later faulting through the rock package produced open fractures in the competent units (quartzite and meta-diorite) and shear zones in the schists and phyllites. Ore mineralization occupies northwest-trending open fractures and particularly the intersections of fracture sets.

Surface impact of mining

From the first silver production in 1913 to the mid-1970s, mining of silver veins in the district occurred in small surface operations or shallow underground mines (<150 m deep) with adit access. Large-scale open-pit mining began in 1977, producing larger volumes of waste rock, particularly at larger mines like Birmingham, Calumet, Onek and Galkeno (Fig. 1). By 1989, in excess of 4.7 million tonnes of waste rock in dumps ranging from 2700 tonnes to 1.4 million tonnes were disposed in 43 sites (United Keno Hill Mines Ltd 1990; unpub. data). Waste rock piles generated by open-pit and other modern mining methods consist of angular boulders of unoxidized, mineralized rock. In contrast, waste piles from earlier underground mining in the oxidized zone are composed of smaller sized rubble. Limonite, pyrolusite, cerrusite and anglesite are among the prominent secondary minerals commonly found in the rubble. In addition to the waste rock piles, a 0.65 km^2 pond impounding tailings from the Elsa mill has been maintained to this date. Drainage from the tailings pond contains elevated zinc, requiring crushed lime to be added periodically to reduce the potential environmental hazard. Small volumes of drainage from workings of many discontinued and abandoned mines in the district also contain elevated metal content, especially zinc, manganese and occasionally cadmium. Today, 22 stations are still being closely monitored by United Keno Hill Mines Limited and/or the regulatory agencies.

Sampling and analytical methods

Both pristine and contaminated streams were sampled during spring freshet (mid-June) and in the fall (late August) to determine the extent of metal contamination of water courses resulting from mining activities and to assess aqueous metal transport and attenuation mechanisms. At each sampling site, field pH, Eh, conductivity and temperature were measured and a 1-l unfiltered water sample was collected. At the end of the day, each water sample was filtered through a 45-μm cellulose acetate filter and two 100-ml aliquots were saved, one for sulfate analysis by ion chromatography and the other, preserved with 2 ml of nitric acid, for dissolved metal analysis by induction-coupled plasma spectrography (ICP). The remainder of the sample was used for alkalinity determination by titration. The pH of the water samples was also measured again to detect any discrepancy between the field- and camp-measured values. This was to confirm that no significant change in aqueous chemistry had taken place during sample transport from the sampling site back to the camp. To shed light on long-term variations in water chemistry, historical monitoring data from selected sites are also examined and compared with the new data set.

To evaluate the role of sediments in attenuating metal transport and to determine the mobility of metal contaminants under surficial conditions, stream sediments and tailings were sampled at selected sites for examination and analyses. Grab samples of about 1 kg in weight and sediment cores of 2.5 cm and 6.3 cm diameter were collected using a plastic scoop, a stainless steel coring tube with a plastic sleeve and a steel hand auger, respectively. Since fine-grained sediments usually dominate water-mineral interaction occurring at a natural site (e.g. Horowitz 1991), only the -180-μm portion of the collected samples was subjected to various analyses. These include trace element analysis by ICP, mineral identification by powder x-ray diffractometry, examination of mineral grain morphology by scanning electron microscopy and sequential extraction analysis for five heavy metals (As, Cd, Cu, Pb and Zn) commonly found in the mining district. The procedure involved in the sequential extraction analysis has been described by Tessier and others (1979). In the analysis, the chemical partitioning of the elements of interest into five fractions (namely, the exchangeable, carbonate-bound, iron and manganese oxide-sorbed, organic-and-sulfide-bound, and, strong acid-leachable fractions) is determined in the order of increasing difficulty of remobilization in the surface environment.

Results

Water chemistry

As an illustration of the nature and extent of metal leaching resulting from past mining activities in the district, Table 1 shows the water chemistry of discharge during spring (mid-June 1993) from the adits of the Onek, Galkeno 900, No Cash and Silver King mines, seepage at the toe of a waste rock dump at the Ruby 200 Mine and a standing pool of water in the old workings of the Rio Plata property. Compared to the pH range of 7.5–8.2 in water courses far away from mine workings (Davidge and Mackenzie-Grieve 1989), these mine waters are depressed to varied extents in solution pH. The seepage at the toe of the waste rock dump of the Ruby 200 Mine in particular is acidic in character. It also contains elevated levels of dissolved Al, As, Sb, Cd, Co, Ni, Mn and Zn. On the whole, acid drainage occurs rarely in the mining district and the Ruby 200 waste rock dump remains dry throughout most of the summer. Despite the near-neutral pH values, water samples from the other mine workings are, however, not devoid of metal contaminants. The discharges from the Onek, Galkeno 900, Rio Plata and No Cash mines all show anomalous contents of dissolved Zn, Mn and Cd. The discharge from the Silver King Mine contains elevated dissolved Fe and anomalous dissolved Cu, Cd and Zn. Most of the dissolved Fe apparently occurs as reduced iron (i.e. Fe^{2+}) prior to discharge. This is evident from the deposition of ferric hydroxide near the discharge point and detection of the same in an unpreserved sample which gave a laboratory-measured pH of 5.2. The slow oxidization of Fe^{2+} to Fe^{3+} by atmospheric oxygen coupled with the hydrolysis of Fe^{3+} to precipitate ferric hydroxide resulted in a subsequent depression of the solution pH by 1 pH unit in about 2 days.

To illustrate the seasonal variation of water chemistry and metal attenuation along a surface stream, two examples are addressed below with the aid of accompanying diagrams.

Figure 2a compares the selected water chemistry of No Cash Creek along the flowpath in mid-June and in late August 1993. No Cash Creek flows through boreal forest on till and schistose bedrock with drainage from No Cash mine entering the stream above Station NC-2 (Fig. 1). During spring freshet (mid-June), the dissolved Zn and Cd concentrations were nearly twice as great as those in

Table 1
Water chemistry at selected old mine workings during spring freshet, mid-June, 1993

mg/L	Onek	Galkeno 900	Rio Plata	Ruby 200 (toe of waste pile)	No Cash	Silver King
Al	<0.005	<0.005	<0.005	2.49	<0.005	0.018
Sb	0.18	<0.02	<0.02	0.25	<0.02	<0.02
As	0.1	<0.04	<0.04	0.22	0.08	<0.04
Ba	0.009	0.013	0.018	0.033	0.004	0.017
Be	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Bi	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Cd	2.34	0.0352	2.07	2.72	0.239	0.0486
Ca	212	404	440	125	125	152
Cr	0.003	0.006	0.007	0.01	0.002	<0.001
Co	0.020	0.064	0.096	0.149	0.015	0.044
Cu	<0.001	<0.001	<0.001	0.094	<0.001	<0.222
Fe	<0.003	1.02	<0.003	0.121	<0.003	25.5
Pb	0.026	<0.004	0.013	0.131	0.005	<0.004
Li	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Mg	22.4	42.9	161	63.6	16.7	41.0
Mn	11.1	77.8	51.7	160	18.4	6.60
Mo	0.026	0.016	0.028	0.028	0.012	0.013
Ni	0.04	0.365	0.276	0.621	0.081	0.153
P	<0.02	<0.02	<0.02	0.13	<0.02	<0.02
K	1.12	1.46	2.82	1.85	0.79	1.75
Se	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
Si	8.17	6.35	9.76	15.6	4.38	12.0
Ag	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Na	1.33	1.63	1.69	3.55	0.96	2.16
Sr	0.26	0.48	0.69	0.17	0.14	0.25
Th	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Ti	0.006	0.007	0.006	0.012	0.005	<0.001
U	<0.02	<0.02	<0.02	<0.02	<0.02	<0.02
V	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Zn	96.2	37.6	109	80.6	25.7	3.97
Sulfate	590	1224	1886	951	409	571
pH	7.2	6.9	7.3	5.4	7.2	6.2
Alkalinity (mg/L $CaCO_3$)	159	161	108	1	70	15
Conductivity (µS/cm)	838	1240	1730	1072	543	674

the fall (late August), suggestive of flushing of highly soluble secondary minerals containing Zn and Cd during snow melt. The pH of the stream was slightly lower during spring freshet, while the dissolved sulfate content showed little variation. The slight pH depression probably resulted from the oxidation of stored ferrous ion during freeze-up and subsequent ferric hydroxide precipitation upon discharge in spring. The high dissolved Zn introduced by mine water dissipated downstream. The relatively constant dissolved sulfate concentrations argue against dilution as a major attenuation mechanism. Precipitation and/or sorption of the metallic ion onto solid matter along the stream bed and banks are probably the predominant phenomena.

Figure 2b depicts the change in water chemistry observed along the Onek drainage near Keno City (Fig. 1). Station ON-1 is located at the entrance to an old mine portal and ON-2 about 150 m downstream where the surface drainage disappears into ground. Compared to the water chemistry in the fall, drainage during spring freshet was also characterized by a lower pH and higher concentrations of dissolved Zn, Cd and sulfate. In the fall, the dissolved Zn and Cd contents dropped significantly, while the dissolved sulfate concentration only slightly decreased. This again demonstrates that dilution is not a significant metal attenuation mechanism in these small streams.

To illustrate the long-term fluctuation in water chemistry, Fig. 3a and b depicts the August monitoring data on pH, dissolved Zn and Cd for the periods 1982–1993 and 1987–1994 for the No Cash Mine discharge and the Onek adit drainage, respectively. In the case of the No Cash Mine discharge, the pH values did not change much throughout the period from 1982 to 1993 and the dis-

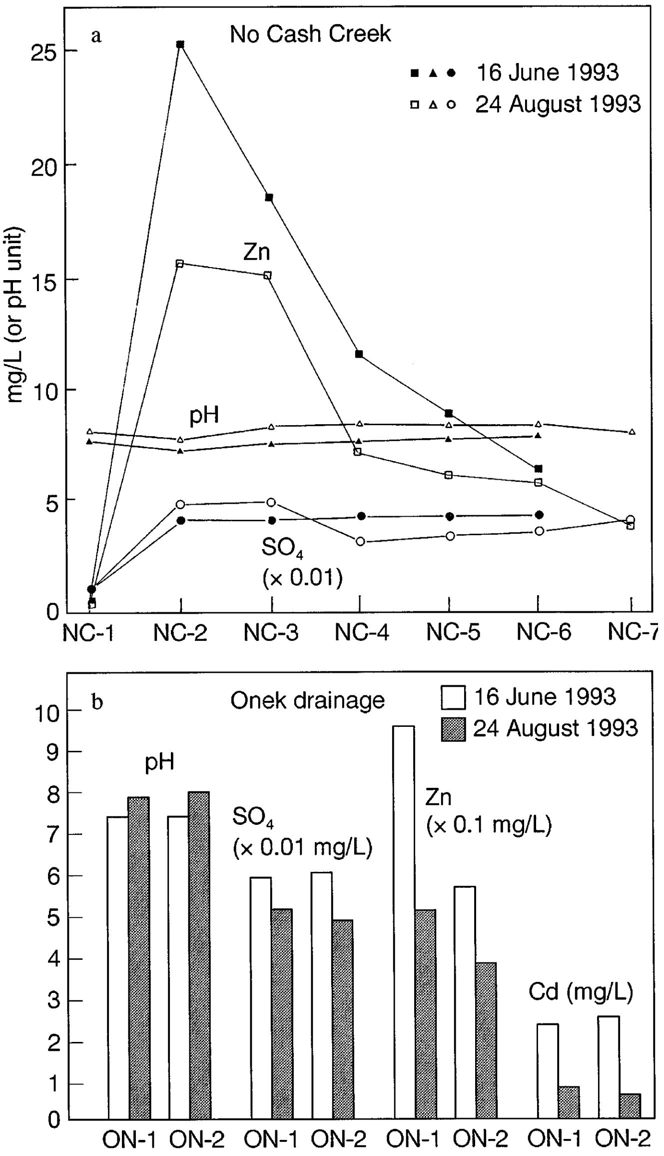

Fig. 2a,b
Comparison of freshet and late summer water chemistry along **a** No Cash Creek and **b** the Onek drainage

solved Zn and Cd concentrations appear to have peaked around 1987. For the Onek adit drainage, the pH remains near-neutral to slightly basic throughout the monitoring period. Ignoring the 1991 spike in the dissolved Zn variation curve, both dissolved Zn and Cd concentrations in the drainage appear to follow an increasing trend in the month of August. We suspect that metal leaching in the source area drained by the existing drainage system has not yet peaked; more metal releases may be expected in the adit discharge in the future.

Soil and tailings geochemistry

Figure 4 compares the concentration of selected trace elements in sediments collected by coring at the termination points of the Onek drainage, No Cash Creek and Star Creek (see Fig. 1 for detailed location). In contrast to the Onek and No Cash drainage systems, Star Creek has not been affected by any mine drainage and its sediment trace element composition does not change with depth. The Pb, Cu, Zn and As concentrations in the stream sediment of Star Creek thus represent the background concentrations of these elements in pristine streams in the study area.

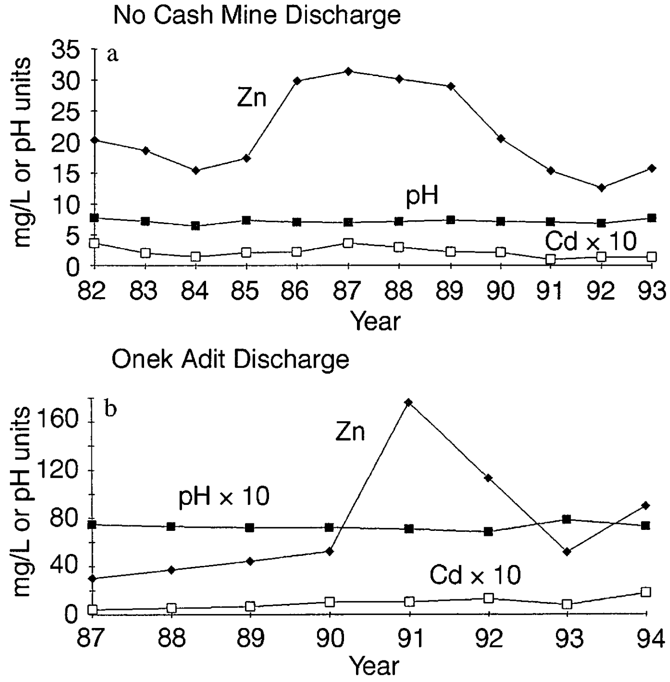

Fig. 3a,b
Long-term fluctuation in pH, Zn and Cd concentrations in mine waters from the August monitoring data of **a** the No Cash discharge 1982–1993 and **b** the Onek adit drainage, 1987–1994. (The missing 1988 data for both data sets are obtained by interpolation of the 1987 and 1989 data)

In the Onek sediment core, Zn and Cd are highest at a depth of about 30 cm below the surface and remain significantly higher (by three orders of magnitude) than the background levels, even at the coring depth of 82 cm. Concentrations of As, Pb and Cu are obviously elevated near the surface but rapidly drop to background level at a depth of greater than about 41 cm. This difference in distribution pattern suggests that Zn and Cd are more mobile than As, Pb and Cu in the Onek drainage system. Along the stream bed, light-yellow secondary mineral precipitates coat organic litter and less commonly rock fragments. X-ray diffraction analysis coupled with chemical analysis indicates that the precipitates consist mainly of hydrozincite mixed with poorly crystalline ferric hydroxide. An examination of the sediment under a scanning electron microscope shows a close association of the precipitate with organic litter (Fig. 5). The formation of hydrozincite and an explanation for the Zn and Cd profile in the Onek sediment core are discussed in a later section.

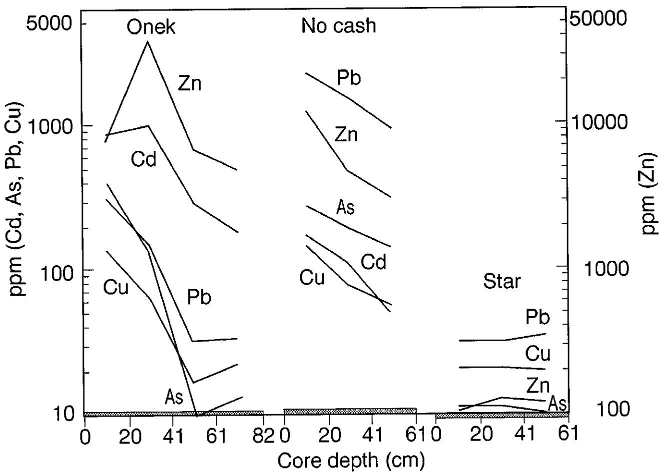

Fig. 4
Comparison of selected trace metal content in sediments at surface terminations of Onek drainage, No Cash Creek and Star Creek

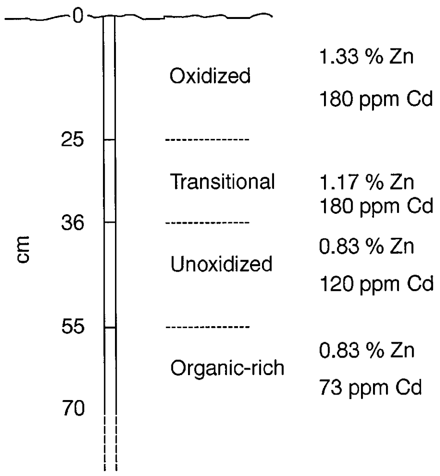

Fig. 6
Variation of Zn and Cd content with depth in a tailings deposit at Elsa, Yukon

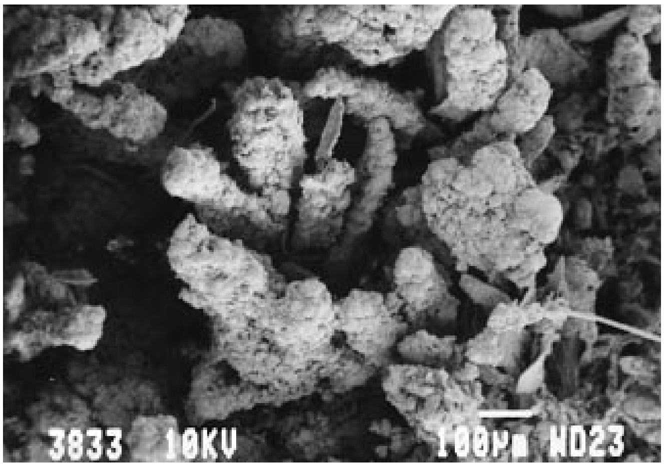

Fig. 5
An electron micrograph showing grains of hydrozincite precipitated on organic litter

Sediments into which No Cash Creek drains also show elevated metal content. The core was sampled deep in the South McQuesten valley where saturated conditions prevail throughout the year and the sediment may not have been completely frozen even in the winter. The concentration of all the five elements depicted decreases rapidly with depth. However, at the maximum coring depth of 61 cm, all these elements are significantly above the background concentrations for the region. Upstream from the coring site, reddish ferric hydroxide locally precipitates on the gravelly stream bed, particularly where the No Cash mine drainage enters the creek. Hydrozincite, however, has not been identified. The lack of organic matter and fine sediments as well as the steeper stream gradient inhibit the formation of hydrozincite in No Cash Creek.

Located also in the South McQuesten River valley downslope from Elsa is a tailings disposal facility where metal mobilization is a concern. Powdered lime is added each spring to control the amount of zinc released downstream. During the dry season, the dry portion of the tailings pond prominently shows a whitish coating on the exposed tailings. Gypsum is the major component of the coating with bianchite (an iron and zinc sulfate) commonly present. Figure 6 shows a concentration profile of Zn and Cd in a sediment core sampled from tailings exposed near the last containment dam. It is worth noting that the two elements are more concentrated towards the surface rather than at depth.

Sequential extraction analysis on sediments

Sequential extraction analysis is a practical chemical partition method that sheds light on the trace element concentration mechanisms in the sediments as well as facilitates prediction of environmental availability of the trace elements concerned (Diks and Allen 1983; Tessier and Campbell 1987). In the Keno Hill mining district, ore mineralization contains varying amounts of Pb, Ag, Zn, Cd, Cu, As and Sb (Lynch 1989). The metals Ag and Sb occurring in area soils and sediments are too low to be measured accurately in the sequential extraction procedure and are thus not included in the analysis. Historical monitoring data (Davidge and Mackenzie-Grieve 1989) in various water courses in the region also suggest that Ag and Sb are generally not an environmental concern.

Figure 7 depicts the partition pattern of Cd, Zn, Pb, Cu and As in the sampled sediments. The diagram is constructed by averaging the results of sequential extraction analyses performed on nine separate sediments collected from sites believed to have been affected to varied extent by mine drainage. These sediments consist of variable amounts of quartz, plagioclase, K-feldspar, chlorite, mica, amphibole, dolomite, siderite, hydrozincite and amorphous iron oxide as well as 0.5–4.0% organic carbon

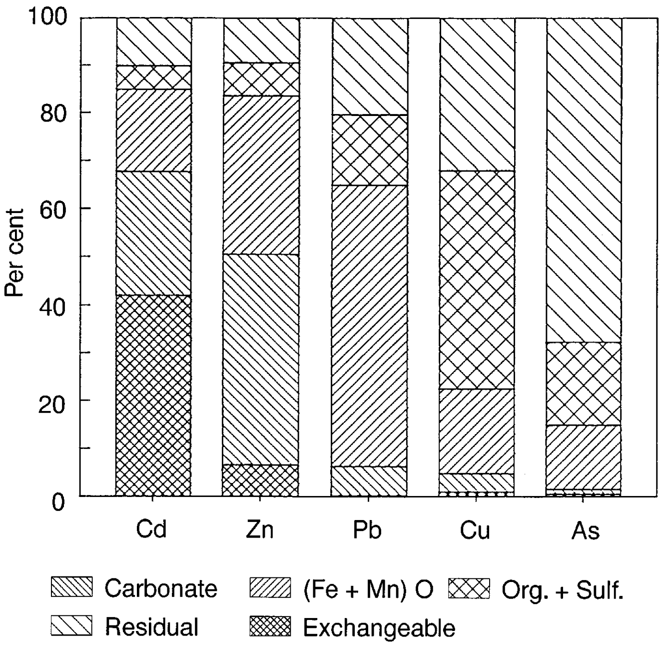

Fig. 7
Partition of Cd, Zn, Pb, Cu and As in sediments from the Keno Hill mining district as revealed by sequential extraction analysis

and up to 0.4% total sulfur. Over 40% of Cd in the analyzed sediments occurs as exchangeable ions loosely adsorbed onto sediment particles with a negative surface charge (e.g. silica, chloritic and illitic clays, hydrated iron oxide). These ions can readily be remobilized with subtle changes in water chemistry. The majority of Zn in the sediments is associated with two fractions, carbonate-bound (about 42%) and co-precipitated with iron plus manganese oxides (about 30%). These observations agree particularly well with the mineralogy and chemical analyses of secondary precipitates found along the Onek drainage which are dominated by hydrozincite and amorphous iron oxyhydroxide. Zn associated with carbonates can readily be remobilized under mildly acidic conditions. The bulk of Pb (60%) found in the sediments is strongly sorbed onto iron and manganese oxides. It can be removed upon destruction of the oxides under highly reducing conditions or in a highly acidic environment ($pH < 3$ for the dissolution of ferric hydroxide).

Organics in the sediments play a significant role in attenuating aqueous transport of Cu in the water courses in the region. Given the extreme climatic conditions of the mining district, it is unlikely that the organic matter occurring in the sediments can readily be oxidized to release the bound Cu. It should be noted that, because of the nature of chemicals used to extract the organic fraction of the sediments, the organics-bound fraction cannot be differentiated from metal sulfides, especially acid-soluble monosulfides. However, in permafrost the formation of metal monosulfides in the sediments is considered to be insignificant. As shown in Fig. 7, a great proportion of Cu in the sediments (30%) is also associated with the residual fraction. The detailed form of Cu occurring in this fraction is not clear but it can be remobilized only by a very strong acid leach; this does not occur in a natural environment.

Most of the As in the sediments (65%) is associated with the residual fraction. As noted by Kwong and Whitley (1993), As is strongly sorbed onto precipitating ferric hydroxide on stream beds or along stream banks. Mineralogical transformation subsequently occurs to render the As immobile as a stable ferric arsenate mineral.

In summary, bound to the sediments significantly as exchangeable ions and in the carbonate fraction, Cd and Zn are highly mobile along water courses in the Keno Hill mining district; in contrast, associated with the more refractory fractions of the sediments in the given environment, Pb, Cu and As are not readily transported far from their source area.

Discussion

The problem of acidic drainage and distribution of metal contaminants that may harm the natural environment is often confronted in the closing of mining sites. Although mines are no longer operating near Keno City, periodic remediation of water discharging from portals and pits continues, as does exploration for new and deeper deposits. Both endeavors can benefit from a better understanding of prevalent water-rock/mineral interactions. It is clear from the water chemistry data that discharges from many mine workings contaminate water courses with trace metals, especially Zn and Cd. Acidic drainage, however, only occurs very locally. Moreover, even along surface streams, natural metal attenuation mechanisms appear to limit the aqueous transport of metal contaminants (Fig. 2). The apparent metal transport and attenuation mechanisms in operation and the reasons for the lack of widespread acid drainage are briefly discussed below.

Metal transport and attenuation mechanisms and their consequences

Dilution does not significantly attenuate metals dissolved in the discharges from the Onek and No Cash mines. The seasonal differences in metal concentrations in the receiving streams suggest formation of soluble secondary minerals during the dry season (including winter) serves as temporary storage of trace metals. This is emphasized by the presence of hydrozincite along the Onek drainage. The temporary metal storage through the formation of hydrozincite by cryogenic precipitation is discussed as follows.

From late spring through fall, microbial growth occurs in small flowing streams like drainage from the Onek Mine and other smaller seeps. Dissolved metals like Zn are sorbed onto the body walls of bacteria which form a microbial mat on organic litter lying on the stream bed. With the onset of winter and progressive freezing, the stream water is increasingly enriched with dissolved constituents resulting from ice segregation (Vogt 1991). Metal ions already sorbed onto the microbial mat provide convenient sites for initial nucleation once the solubility product of a secondary mineral such as hydrozincite is exceeded. Further accumulation of newly precipitated material extends outward from the initial nucleation centre with the result that the shape of the final aggregate approximates that of the plant substrate (Fig. 5). The precipitation of secondary minerals may also lead to the coprecipitation of other metallic ions. For example, the geochemical behavior of Cd is very similar to that of Zn; hydrozincite precipitation will thus result in the coprecipitation of Cd. This relationship is demonstrated by sequential extraction results which show that about 22% of Cd in the sediments are carbonate-bound (Fig. 7). However, hydrozincite formed by cryogenic precipitation is likely to redissolve during spring freshet unless it is rapidly buried. This explains why the surface sediments are less concentrated with respect to Zn and Cd contents than those immediately below (Fig. 4), unless the mineral is precipitated also as a deuteric or groundwater-related phase.

Ferrous iron sorbed onto sediment particles along the stream bed will undergo oxidation to precipitate ferric hydroxide, especially under open water conditions. Extensive iron oxide coatings occur along the Onek drainage and No Cash Creek. As is evident from the results of sequential extraction analyses, iron oxide is an efficient scavenger for many dissolved metals, including the five trace metals studied in the Galena Hill area. Thus, sorption onto precipitating ferric hydroxide is another very important metal attenuation mechanism operating in these small streams and almost all similar streams in abandoned mining districts. Once these tributaries enter larger water courses such as the South McQuesten River, dilution will inevitably play a more significant role in metal attenuation. In these larger water courses, the formation of efflorescent minerals is prohibited by the low metal concentrations resulting from mixing.

In the tailings pond, large amounts of sediments are deposited and unsaturated conditions prevail at least part of the year due to evaporation. Here, translocation processes may be responsible for the redistribution of highly soluble metallic ions. In summer when the evaporation rate is high, water lost from the surface of the tailings deposit is continuously replenished by water from the saturated zone through capillary action. On its upward journey, the replenishing water carries with it dissolved constituents including Ca, Fe, Zn, Cd and sulfate which form efflorescent minerals, namely gypsum and bianchite, on the surface. The concentration of Zn and Cd is therefore highest at the surface, as shown in Fig. 6.

The post-mine, near-surface concentration of metal contaminants in the Keno Hill area has important bearing on future mine-waste disposal strategies if renewed mining is to occur. Any schemes involving an expansion of the existing facilities (for example, the tailings pond) to accommodate new mine waste must consider potential remobilization of the easily soluble secondary products accumulated in the old waste. Capping the old mine waste prior to deposition of new waste on top or disposal of the latter downstream of the former are two alternatives that would avoid potential serious metal leaching problems.

Reasons for lack of widespread acid drainage

Acid mine drainage is a major environmental concern associated with many metal mines. Although sulfide minerals abound in many old mine workings and waste rock dumps of the Keno Hill mining district, drainage rarely becomes acidic. For instance, in the remnant workings of the Rio Plata prospect, copiapiate, an efflorescent iron sulfate hydrate stable only under acidic conditions, was observed to coat siliceous phyllite enriched in fine-grained pyrite. A nearby pond, however, has a pH of 7.3 and the water is highly enriched in Zn, Cd, and sulfate (Table 1). The high concentrations of dissolved metals and sulfate clearly indicate sulfide oxidation. The fact that drainages do not become acidic can be due to some or all of the following.

Firstly, any acidic drainage generated locally by oxidation of iron sulfides or other metallic sulfide minerals with an excess of sulfur over the constituent metal(s) is neutralized in the immediate vicinity by carbonate minerals. The observation of carbonate in nearly all major rock types and the high net neutralization potential of many non-mineralized samples (Kwong and others 1994) support this possibility.

Secondly, in the Rio Plata prospect and other mineralized areas of the mining district, galena and sphalerite commonly occur together with pyrite. In the weathering of a multi-sulfide mineral assemblage, the sulfide mineral with the highest electrode potential is galvanically protected from oxidative dissolution while the weathering of the mineral with the lowest electrode potential is enhanced (Sato 1992; Kwong 1995). Among the three common sulfide minerals pyrite, galena and sphalerite, pyrite has the highest electrode potential followed by galena and then sphalerite (Sato 1992). If these minerals are in contact with each other, sphalerite will be preferentially weathered and oxidative dissolution of pyrite will not occur until all the sphalerite and galena have disappeared. Pyrite is thus galvanically protected by the adjacent sphalerite and galena grains. With a metal-to-sulfur ratio of 1:1, however, the oxidative dissolution of either galena or sphalerite will not lead to net acid generation (Thornber 1975; Alpers and Brimhall 1989). Thus, the occurrence of acid drainage is delayed. This hypothesis explains the unexpected near-neutral pH despite high dissolved metal and sulfate concentrations in the ponded water in the Rio Plata workings. The hypothesis is also supported by two other field observations:

1. Acidic drainage was detected at the toe of a waste rock dump of the Ruby 200 Mine (mid-June 1993). Here, siliceous phyllite with abundant pyrite constitutes the bulk of waste rock in the surface layers of the dump and neither carbonate nor sphalerite is visibly present. How-

ever, the waste pile apparently contains abundant sphalerite and manganiferous siderite at depth, the leaching of which by acidic drainage generated near the surface has given rise to the elevated dissolved Zn, Cd and Mn content in the seepage detected at the toe of the dump (Table 1).

2. In a low grade ore stockpile at the Husky SW Mine, the secondary mineral efflorescence melanterite was observed forming on fine-grained bands of pyrite and possible marcasite. The stockpile has been exposed to the atmosphere for less than 3 years and again little sphalerite or galena have been identified associated with the iron sulfides. The presence of melanterite indicates that (i) the iron sulfides are highly reactive and (ii) local acidic conditions prevail. In absence of a contacting mineral with a lower electrode potential to offer cathodic protection of the reactive iron sulfides, this stockpile, if left exposed, will continue to readily generate acid.

The possible delay in occurrence of acid rock drainage due to galvanic protection of pyrite from oxidative dissolution has important implications to the remediation of old mine workings in the mining district. To avoid intensive leaching of metals, highly reactive rocks with little buffering capacity should be identified and properly disposed before they generate acid. Recognition of precursor minerals like melanterite is a useful field guide to assess the acid generation potential of a waste pile. Reactive mine waste with a high proportion of readily soluble oxidation products needs to be incapsulated in an impermeable structure or reprocessed to reduce the concentrations of metal contaminants. Fresh reactive mine waste can be disposed of in an environment like a wetland setting that discourages sulfide oxidation. Burial in the wetlands of the South McQuesten River valley to take advantage of the insulating effect of discontinuous permafrost and the locally reducing conditions is a potential waste management strategy that deserves further investigation.

Conclusions

The following conclusions can be drawn with regard to the post-mine metal transport and attenuation in the Keno Hill mining district.

1. Discharge from many old mine workings contain elevated concentrations of dissolved metals, especially Zn, Mn and Cd. Metal loadings are especially high during spring freshet, resulting from the dissolution of efflorescent minerals formed during the dry seasons including winter.

2. Prominent metal attenuation mechanisms operative in small streams include cryogenic precipitation, coprecipitation, sorption and rarely dilution. Dilution, however, is the major metal attenuation mechanism in larger water courses.

3. Despite evidence of active sulfide oxidation, acid mine drainage is currently not widespread due to neutralization by carbonate minerals in the country rock and galvanic protection of a significant amount of pyrite from oxidative dissolution.

4. To prevent a potential onset of intense acid generation and metal leaching, reactive mine waste should be identified early and disposed of in an environment which discourages sulfide oxidation.

5. The near-surface concentration of metals in the mining district dictates that, if the existing waste disposal facilities were to be expanded to meet the need of renewed mining development, either the old waste should first be safely capped or new mine waste be disposed downstream of the existing mine waste. Otherwise, metal leaching from old mine waste is inevitable.

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