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**Analytical Results and Conceptual Model of Mine Drainage at the Holden Mine,
Chelan County, Washington**

By

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ABSTRACT-The Holden orebody is a relatively low-grade, Cu-Zn-Ag-Au, Kuroko-type volcanogenic massive sulfide deposit (VMS) located within the crystalline core of the northern Cascade Range, north-central Washington. The abandoned mine and related workings lie adjacent to Railroad Creek, a major tributary of Lake Chelan (a large fjord lake some 20 km to the east). Because of their pyrite- and sulfide-rich nature, massive sulfide deposits such as Holden have an unusually high acid-generating capacity. Under oxidizing conditions, water draining these deposits can react with the sulfides to form acidic, metal-rich waters that represent potentially significant sources of acid and metal-loading in the environment. Detailed hydrogeochemical studies conducted at Holden by the U. S. Geological Survey (USGS) as well as preliminary investigations undertaken by Dames & Moore on behalf of Alumet Inc., identified numerous mine-related seeps and flows of widely diverse compositions at the site. Broadly defined, this discharge can be categorized into two discrete groups consisting of : (1) acidic to strongly acidic, Fe-dominant seeps at or near the base of the tailings piles; and (2) weakly acidic, base-metal-rich effluent draining the mine, mine workings, and assorted waste piles and prospects found generally west of the tailings. The mine-related discharge is further characterized by a distinct seasonal variation in both chemical composition and magnitude of flow. In general, the lowest pH and highest dissolved solid concentrations (and total dissolved mass) coexist with peak flow conditions associated with the spring runoff. As the flow and circulation of water progressively abates through the summer and fall, pH levels gradually increase, whereas the concentration and mass of dissolved metals decline markedly. According to the site conceptual model, the chemical makeup of Holden's acid drainage can ultimately be traced to a number of dominant controls that are largely a function of ore deposit geology (e.g. pyrite content, structural characteristics, etc.). However, seasonal variation in mine water chemistry is for the most part attributed to the dissolution and hydraulic flushing of soluble secondary minerals in the spring and their precipitation from saturated and supersaturated solutions in the summer and fall.

INTRODUCTION

This short paper and accompanying conceptual model attempts to provide Federal and state regulators, land-use planners, and other interested parties a practical understanding of the major processes which are believed to effect the evolution of acid-mine drainage at the Holden mine. Scientific jargon and complex geochemical processes are intentionally kept to a minimum or are greatly simplified; hopefully without compromising scientific integrity. In this respect, the conceptual model is based on established geochemical principles as well as field and laboratory observations made at Holden and elsewhere. However, many of our perceptions regarding the Holden site are conjectural in nature, and the model cannot be considered definitive or conclusive. In addition, the report provides the tabulated analytical results (tables 1-3) and sample localities (figure 2) for mine related effluents collected during the September 1996 U. S. Geological Survey (USGS) Holden site investigation. Analytical results from previous USGS geochemical studies at Holden are found in Kilburn and others, 1994; Kilburn and Sutley, 1996; and Kilburn and Sutley, 1997. The mineralogy of secondary sulfate minerals collected at the mine from 1994 -1996 are also included in this report.

Each mine site is a unique geologic and geochemical entity, yet the environmental ramifications of acid-mine drainage remain a common and disturbing factor in past and present mineral development. In recent years, reliable accounts linking contaminated mine water with declines in aquatic insect populations, periodic fish kills (Arnekleiv and Storset, 1995) and even cattle deaths (Webster and others, 1994) have provoked considerable public sentiment regarding the nation's water quality and stability of its aquatic ecosystems. In this regard, the United States and other industrialized countries have made a concerted effort to curb mine-related pollution by encouraging modern mining methods and enacting strict environmental codes or regulations to oversee active and future mining endeavors. Nevertheless, the enigma of acid-mine drainage persists, at a magnitude greater than once believed, in the form of what Allan (1995) termed "historical pollution" associated with inactive or abandoned mine sites. Of particular concern are volcanogenic massive sulfide deposits (VMS) such as Holden, a deposit type that has produced some of the most acidic, metalliferous mine drainage on record (Alpers and Nordstrom, 1991). Because of their pyrite- and sulfide-rich nature, VMS deposits have an unusually high acid-generating capacity. Under oxidizing conditions, water draining waste piles, underground workings, and unmined ore zones of such deposits can react with the sulfides to form acidic, metal-rich waters that represent potentially significant sources of acid and metal-loading in the environment; jeopardizing not only local water quality, but neighboring aqueous and terrestrial ecosystems as well. Moreover, Holden, like many sulfide-rich deposits, is characterized by an abundance of metal salts that readily dissolve during episodes of wet weather or heavy runoff (e.g. snowmelt), liberating additional amounts of acid and metals to the surroundings.

Recent studies at the Holden complex were undertaken by the USGS (1994-1996) and Dames & Moore (1997) (at the request of Alumet Inc.) to determine the nature and extent of the mine's acid drainage and characterize its aftereffects on the local Railroad Creek watershed. In brief, these studies revealed a dynamic and complex hydrologic regime, typified by a wide-range in mine effluent compositions that commonly fluctuate chemically with the season. Although most of the contaminated discharge can be identified with a variety of point sources, the mine-related effluents have been broadly categorized by Dames & Moore into two distinct groups based on chemical similarities and general proximity. These designated groups are: (1) the East Area, consisting of strongly acidic, Fe-dominant seeps that surface at the base of the three tailings piles; and (2) the West Area, consisting of weakly acidic, base-metal rich water draining the mine, mine workings, and various waste piles and prospects located generally west of the tailings (Dames & Moore, preliminary and unpublished data, 1998). For simplicity, this report will adopt this arrangement. In addition, the paper gives particular emphasis to the spring runoff because of its obvious impact on mine drainage compositions and ultimately neighboring Railroad Creek. The portal discharge also receives special attention in view of its high base-metal content and the myriad of geochemical processes that govern its development. Furthermore, using the portal drainage section as a general guide, inferences can then be made regarding mine drainage elsewhere at Holden without resorting to undue redundancy.

Site Description and Mining History

The Holden deposit is sheltered in a U-shaped, glacially modified valley located immediately east of the divide that forms the serrated crest of the northern Cascade Range of north-central Washington State. The mine and related workings border Railroad Creek, one of the larger watercourses that feeds Lake Chelan, a large landlocked fjord some 20 km east of the orebody (figure 1.). Topographic relief is great in the Holden area (approximately 2,500 m) with the mine surrounded by towering peaks and hanging valleys. In some of the higher basins and cirques, small glaciers persist and mark the headwaters of Railroad Creek's major tributaries, including Copper Creek, Big Creek, and Holden Creek. The valley floor is covered by a deep overburden (mostly glacial debris and talus) that is largely hidden by thick underbrush and scattered stands of timber consisting of fir, cedar, spruce, and balsam. Most of the valley walls are abrupt, with rock exposures generally replacing timber above 1,200 m. The climate is temperate and typified by warm dry summers and cold wet winters. Mean annual precipitation at Holden is about 90 cm (35 in), mostly in the form of snow. Because the earliest snowmelt (usually May in the Holden area) has a tendency to be enriched in ionic solutes (Harrington and Bales, 1998), the entire Railroad Creek basin is probably subject to natural metal-loadings during the spring runoff. Access to the site is limited to regularly scheduled boat service out of Chelan or by chartered floatplane to the port of Lucerne, a former resort community on Lake Chelan. From Lucerne, a graded dirt road negotiates the steep Railroad Creek valley to the mine.

Mining possibilities in the Railroad Creek watershed were first recognized in the summer of 1887, when a location engineer in search of potential routes for the Great Northern Railroad reported and described the weathered, rust-colored gossan marking the eventual site of the Holden mine. As accounts of these altered rocks inevitably spread, wholesale prospecting efforts began in earnest, with initial claims being staked in the Railroad Creek valley in 1892. Over the next 36 years a number of individuals and syndicates held options on the Holden deposit, although efforts to develop the claim proved ineffectual. In 1928 the Britannia Mining and Smelting Co., a subsidiary of the Howe Sound Co., acquired the property. Administration of the claims and authority to conduct further exploration was promptly passed to another subsidiary, the Chelan Copper Mining Co. Rapid development soon followed, including the tunneling and sinking of shafts, the erection of the mill facility to process the ore, and the construction of the company town of Holden to accommodate the miners and their families (Youngberg and Wilson, 1952; McWilliams, 1958). In 1937, the subsidiary relationship was dissolved and the Howe Sound Co. took possession of the property and began active production in 1938. The mine discontinued operations in 1957 because of escalating production costs and a decline in the copper market. Although the ore was of relatively low tenor (averaging roughly 1.1 percent Cu, 0.2 percent Zn, 0.2 oz/short ton Ag, and 0.006 oz/short ton Au) (Nold, 1983) over 212 million pounds of Cu, 40 million pounds of Zn, 2 million ounces of Ag, and 600 thousand ounces of Au were extracted from 10 million tons of ore (McWilliams, 1958). At present, the mine site consists largely of mill tailings, waste dumps, portals and shafts, a partially dismantled mill and other surface structures (figure 2). However, the community of Holden, located on the north side of Railroad Creek

opposite the mine complex, remains quite active and serves as an interdenominational church retreat administered by Holden Village Inc. (formerly Lutheran Bible Institute).

Geologic Setting

The Holden mine lies within the crystalline core of the northern Cascade Range, a region characterized by three major northwest-trending tectonostratigraphic units: the Nason, the Swakane, and the Chelan Mountains terranes. The Holden orebody is contained within the Chelan Block of the Chelan Mountains terrane (Dragovitch and Derkey, 1994). The oldest metamorphic rocks exposed in the region, the Swakane Biotite Gneiss, is considered early Paleozoic or older based on zircon dating. This unit consists primarily of biotite gneiss interbedded locally with hornblende schist and gneiss, clinozoisite-epidote gneiss, and quartzite (Cater, 1982). Overlying the Swakane Biotite Gneiss is a complex series of upper Paleozoic metamorphic rocks referred to as "younger gneissic rocks of the Holden area" by Cater and Crowder (1967). This highly folded sequence includes schistic and gneissic rocks of varying compositions along with intercalated quartzite and marble lenses. Unconformably overlying the metamorphic units are shale, arkosic sandstone, and conglomerate of the Eocene Swauk Formation (Cater, 1982).

Igneous rocks in the northern Cascade Range vary considerably in age and composition. Pre-Tertiary ultramafic rocks of uncertain age mostly are found as small masses consisting of gabbro, hornblende, and peridotite that are locally altered to serpentine. In addition, ultramafic rocks of probable Eocene age outcrop on the surface and in the underground workings of the Holden mine. These younger ultramafic rocks are composed of larger masses of hornblende and hornblende peridotite and hornblende gabbro (Cater, 1982). Regionally, the most common igneous rocks are Mesozoic metamorphosed granitic intrusives (orthogneisses) (Nold, 1983) including the Triassic Dumbell Mountain plutons (the oldest granitoid rocks in the region with a radiometric date of about 220 m.y.) which form a narrow belt of northwest trending rocks of greissic hornblende-quartz diorite and quartz diorite gneiss. Tertiary intrusions ranging in age from early Eocene to Miocene are also prevalent in the region. These Tertiary intrusives are largely granodiorite in composition, but can range from gabbro to quartz monzonite (Cater, 1982).

The Holden orebody is interpreted as a metamorphosed, Kuroko-type VMS deposit exhaled in a late Triassic island arc setting (Dragovitch and Derkey, 1994). The deposit is strata-bound within a sequence of steeply dipping, high-grade metamorphic rocks, largely consisting of calc-silicate gneisses and amphibolites. These rocks are more or less andesitic in chemical makeup, suggesting andesitic volcanics and related volcaniclastic sedimentary rocks as likely protoliths. The immediate host of the mineral deposit is a pyritic, sericite-quartz schist sequence within the high-grade metamorphic rocks. Exposures of the ore-bearing schist, which range from 90 to 180 m in thickness, can be traced for at least 5 km at the surface. The orebody is stratiform within the schist unit and displays the well developed zoning typical of VMS deposits, with a lower copper-rich or original footwall and a zinc-rich upper or original hanging wall. This primary zoning has endured the ravages of high-grade metamorphism as well as intense

deformation, which has overturned the deposit, resulting in a copper-rich zone structurally above a zinc-rich zone (Nold, 1983). Principal ore and ore-related minerals found at Holden include pyrite, pyrrhotite, chalcopyrite, sphalerite, and native gold. Accessory galena, magnetite, and molybdenite are also present. Gold is spatially associated with chalcopyrite in the structural hanging wall, whereas silver mostly occurs with sphalerite in the structural footwall (McWilliams, 1958). Mineralization is for the most part disseminated, although massive ores are found locally in the zinc-rich zone (Nold, 1983).

Summary of USGS Geochemical Investigations

The primary focus of USGS studies at the Holden mine was to: (1) describe the environmental behavior of a historically mined massive sulfide deposit as it undergoes weathering in a temperate climate; and (2) provide the U. S. Forest Service (USFS) with information regarding the nature and scope of the site's mine-related discharge. With this emphasis, the USGS conducted a reconnaissance geochemical study in and around the Holden complex in July 1994 to rapidly identify, at a relatively low cost, the probable sources and general chemical makeup of waters draining the abandoned mine (Kilburn and others, 1994; Kilburn and others, 1995a,b). A detailed follow-up study was concluded the following summer (July 1995) in order to assess the extent of and further characterize the contamination earmarked by the earlier investigation (Kilburn and Sutley, 1996). Additional geochemical surveys were completed in May and September of 1996 to address seasonal variation in mine water chemistry. Analytical results and interpretation of the May 1996 study are given in Kilburn and Sutley (1997). A complete listing of the analytical results (tables 1-3), sample locality map (figure 2), and descriptions of field and laboratory methods employed for the September 1996 study are provided in this report.

Field and Laboratory Methods (September 1996)

In September 1996, mine-related discharge and surface flow from Railroad and Copper Creeks were collected at or adjacent to the Holden complex in polypropylene bottles previously rinsed with 10 % HNO_3 . At each site a 60-mL sample, filtered through a 0.45 μm acetate membrane filter and acidified with concentrated HNO_3 , as well as an untreated 250-ml sample were collected. On-site measurements of pH, specific conductance, and temperature were also taken. The untreated water samples were analyzed for selected anions (F^- , Cl^- , and SO_4^{2-}) by the method of Fishman and Pyen (1979) using ion chromatography. Filtered and acidified water samples were analyzed for major, minor, and trace elements by the inductively coupled plasma-mass spectrometry (ICP-MS) technique of Meier and others (1994) and by inductively coupled plasma-atomic emission spectrometry (ICP-AES) using the Briggs (1990) procedure. The ICP-MS technique is regarded as a trace method, and is generally preferred in analyzing extremely low concentrations of dissolved metals and other elements in the low and sub-ppb range (e.g. rare earth elements) that may be dissolved in mine-related effluents, and is exceptional in defining the character of primitive or largely uncontaminated waters such as creeks and streams. Conversely, ICP-AES methodology is considered more reliable at

determining the high to extreme concentrations of Fe, Al, the base-metals and other elements that often accompany degraded effluents such as acid-mine drainage.

Tables 1-3 record the analytical results for each of the water samples collected during the September 1996 field season. The mineralogy of secondary sulfate minerals identified at the Holden site in 1994, 1995, and 1996 is found in tables 4, 5, and 6 respectively. In data tables 1-3, if a specific element was analyzed for but not detected, a "less than" symbol (<) was entered in front of the lower limit of determination. On the other hand, if an element was measured above the highest reporting value, a "greater than" symbol (>) was entered in the tables in front of the upper limit of determination.

DISCUSSION AND CONCEPTUAL MODEL

The following interpretative analysis, or conceptual model, is based on observations and data compiled by the USGS (referenced above) as well as preliminary data provided by Dames & Moore on behalf of Alumet Inc. Seep and surface water quality data obtained from these independent investigations proved remarkably compatible (especially considering that the USGS utilized sampling methods and protocols better suited to reconnaissance geochemical surveys as opposed to the more rigid Quality Assurance/Quality Control (QA/QC) applications required of Dames & Moore) and can be used interchangeably in a nonrigorous manner to illustrate prevailing conditions at Holden. Because Dames & Moore collected important, site-specific flow rate information not included in the USGS studies, Dames & Moore water data is preferentially applied in this report when characterizing mine-related drainage (and cited as "preliminary and unpublished data"). A word of caution, this paper frequently refers to mine effluent compositions in terms of concentration and/or mass; they are not equivalent quantities or units. To avoid confusion, concentration simply concerns the relative amounts of solute (in this case, dissolved metals) and solvent (water) in Holden's mine drainage. Mass applies to the total amount of dissolved matter in a solution, and is not a function of volume.

Major Controls of Mine Drainage at the Holden Site

The evolution of the diverse, metalliferous Holden discharge is contingent on many complex, often obscure geochemical and geologic processes. Because these processes or controls may be unique to each mine site, a rigid "off-the-shelf" approach to characterization and understanding would be impractical and possibly misleading. With this caveat in mind, a short description of the dominant factors controlling the development of the site's mine drainage compositions was devised based on the non-specific guidelines outlined in Plumlee and Nash (1995). These controls, which are largely a function of ore deposit geology, are summarized below.

Geologic Controls

- **Pyrite content.** Holden, like most VMS deposits, is characterized by an abundance of pyrite. The oxidation of this mineral not only releases large

quantities of Fe to the environment, but also has the potential to generate the most acidic mine drainage found in nature. An obvious manifestation of this weathering process is found at the base of the mill tailings, where strongly acidic, Fe-rich seeps are common. Because of its importance, a brief profile of pyrite oxidation is given in the next section.

- **Host rock buffering capacity.** Host rocks associated with the Holden deposit have a low buffering capacity which is consistent with most VMS models. This not only translates into lower pH solutions, but also tends to stabilize the dissolved metal content of mine-related discharge by restricting pH dependent precipitation and metal-partitioning reactions.
- **Structural and physical characteristics of the mine and orebody.** Extensive underground workings and fractured host rocks associated with the Holden mine permit easy access for weathering agents such as circulating groundwater and atmospheric oxygen, thereby promoting oxidation and metal leaching reactions.
- **Base-metal sulfide content.** At Holden, mine related effluent west of the tailings impoundment's is characterized by relatively high levels of dissolved Cu, Zn, and Cd. The amounts and proportions of these heavy metals in solution can be directly traced to the chemical weathering of the base-metal sulfides chalcopyrite (Cu) and sphalerite (Zn, Cd) inherent in the Holden orebody.
- **Secondary mineralogy.** The Holden complex is characterized by an excess of soluble secondary sulfate minerals derived from sulfide weathering and related acid-generation (including Fe, Cu, and Zn phases). The partial or complete dissolution of these efflorescent metal-salts (which store acid and metals in the solid state) during periods of cyclic runoff or seasonal storm events greatly increases the acidity and metal content of mine-related discharge, which in turn, may impact nearby Railroad Creek.

External Controls

- **Climate.** Holden experiences highly seasonal fluctuations in weather that are typically associated with Temperate Mountain Zones, including cold wet winters and hot dry summers. These conditions favor sulfide oxidation, the development of metal salts, and provide seasonal pathways for metals migration.
- **Mining and milling methods** practiced at Holden certainly encourage and accelerate natural weathering processes by providing easy access to sulfide minerals in the form of extensive underground workings, mill tailings, waste piles, and even concentrated ore material.
- **Topographic relief** is great in the Holden area, influencing not only the shape and position of the local ground water table, but also controlling to some degree the

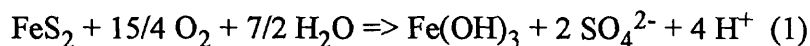
extent to which the mine and mine workings are exposed to oxygenated ground and surface waters.

Geochemical Controls

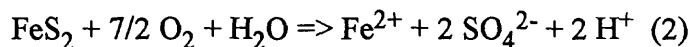
- **Mineral precipitation and sorption** reactions play an active role in substantially tempering the dissolved metal content of Holden's mine drainage. The formation of Al- and Fe-rich flocculent material in the portal drainage is a highly visible example of these metal partitioning reactions. Because of their impact, a short commentary regarding sorption processes is detailed later in this report.

Oxidation of Pyrite

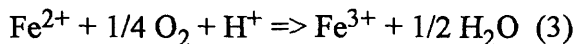
The major cause of acid mine drainage, surface and ground water contamination, and the formation of acid sulfate soils at the Holden site can ultimately be traced to the oxidation of pyrite. This is a complex biogeochemical process not thoroughly understood in natural settings, involving a number of oxidation-reduction reactions enhanced by bacterial catalysis. Because of its profound impact, a brief overview of this chemical weathering phenomenon is considered an essential complement to any conceptual model addressing mine drainage at Holden. The overall pyrite oxidation process is frequently described by the following reaction:



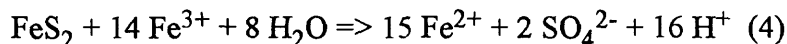
in which insoluble ferric hydroxide and sulfuric acid are produced by the reaction of pyrite and water, in the presence of oxygen. For every mole of pyrite that is oxidized, four moles of H^+ are released to solution. Few reactions in nature produce this amount of acidity. However, this symbolic representation is somewhat misleading as the reaction does not proceed as directly or as simply as the equation suggests. Pyrite oxidation actually progresses via a sequence of intermediate steps as summarized by:



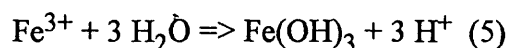
in which pyrite is initially oxidized by oxygen, liberating S^0 that is then oxidized to sulfate, creating an acidic ferrous sulfate solution. The reduced or ferrous iron (Fe^{2+}) in reaction (2) may then be oxidized to ferric iron (Fe^{3+}) as shown by:



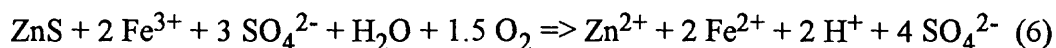
Ferric iron produced in reaction (3) may now act as an oxidant, perpetuating and intensifying the oxidation of pyrite (Garrels and Thompson, 1960; Smith and Shumate, 1970) as indicated by the following equation:



Reaction (4) is rapid (Alpers and Nordstrom, 1991) but limited by conditions imposed by the rate determining step, reaction (3) (ferrous to ferric). Under weakly acidic and alkaline conditions, most of the ferric iron produced by reaction (3) is lost by precipitation of insoluble ferric hydroxide and oxygen remains the dominant oxidizer of pyrite. In more acidic environments the rate of ferric iron hydrolysis drops, and at pH <3 ferric iron is the principal oxidant of pyrite. Oxidation of ferrous iron by oxygen proceeds very slowly at this point, with pyrite (reaction 4) reducing ferric iron faster than it can be replenished. If enough pyrite is present, all the ferric iron will be reduced and reaction (4) abruptly terminated (Nordstrom, 1982). However, acidophilic, iron-oxidizing bacteria (*Thiobacillus ferrooxidans*) may act as catalysts and accelerate the ferrous oxidation rate up to six orders of magnitude (Lacey and Lawson, 1970; Singer and Stumm, 1970), so that the regeneration of ferric iron is greater than its reduction by pyrite, making pyrite oxidation under these conditions (reaction 4) a self-sustaining process. When the pyrite is completely weathered or oxidized, the remaining ferric iron is quickly hydrolyzed, producing insoluble iron hydroxide:



The chemical weathering of pyrite generates large amounts of sulfuric acid and ferric sulfate, strong solvents that not only perpetuate the oxidation of pyrite, but also leach and hasten the oxidation of other metal sulfides such as sphalerite (Guilbert and Park, 1986):



Reaction (6) is inferred to take place at the Holden site and is considered a prominent factor in determining the composition of the areas mine drainage.

West Area

The West Area, located for the most part west of Tailings Pile 1 and the Copper Creek diversion (figure 2), is characterized by weakly acidic, base-metal rich drainage with little or no measurable Fe. This discharge is highly seasonal both in chemical composition and volume of flow. The West Area is further marked by a plethora of soluble secondary sulfate minerals (including Fe, Cu, and Zn phases) (tables 4-6) that are found as disseminations or crusts near the base of the tailings and in the vicinity of the lagoon, or as mineralogically complex aggregates in the abandoned mill (Kilburn and Sutley, 1996; Kilburn and Sutley, 1997). Fluctuations in water chemistry suggest that the underground mine workings may also host an abundance of soluble metal-salts. In the spring, the West Area is commonly overrun with seasonal seeps and overland surface flows. However, this section will only address major point sources of migrating drainage including: (1) the mine portal; (2) the mill and surrounding waste piles; (3) the lagoon area; and (4) the Honeymoon Heights drainage area (figure 2).

Portal Water

Over much of the year, mine drainage flowing from Holden's main portal (1500 level) is believed to be the major point source of base-metal loadings to Railroad Creek (figure 2). Field and analytical data compiled by Dames & Moore in 1997 suggest that as much as (in kg/day) 0.40 Cd, 20 Cu, and 74 Zn may enter Railroad Creek via the portal drainage during discrete periods of the spring runoff. The exact origin of the portal effluent is uncertain, although much of the water is probably derived from upgradient meteoric sources (including snowmelt, rainfall runoff, and direct precipitation) that gain entry to the mine through faults, fractures, and mine related surface apertures (Dames & Moore, preliminary and unpublished data, 1998).

Although an understanding of the many processes (chemical and physical) that influence the composition of the migrating mine waters is far from complete, sufficient data is available to characterize this discharge and make some general inferences regarding its evolution, including primary sources and potential sinks of dissolved metals.

Characterization

Water emerging from the main portal of the mine (1500 level) proceeds rapidly downhill nearly a quarter mile before flowing directly into Railroad Creek. The volume or magnitude of the portal discharge is highly seasonal, with peak flow occurring during the snowmelt-triggered spring runoff and visibly ebbing in the fall and winter months as upslope conditions stabilize. Perennially suspended in this outflow or adhering to rocks and debris the length of the drainage is a thick, tan-white, flocculent substance (floc) identified chemically as amorphous Al hydroxides intermixed with lesser amounts of Fe hydroxide precipitates (Kilburn and others, 1995a,b; Kilburn and Sutley, 1996).

Analysis and interpretation of portal effluent sampled by Dames & Moore in May, July, and September of 1997 depict an Fe-poor, base-metal rich system that exhibits significant seasonal variation in dissolved metal content (both in concentration and mass), pH, and degree of base-metal attenuation between the mine and Railroad Creek (Dames & Moore, preliminary and unpublished data, 1998). These observations are compatible with historic USGS findings (Kilburn and Sutley, 1996; Kilburn and Sutley, 1997). Of particular interest is the drastic change in water chemistry between May and September. This span is marked by a progressive decline in dissolved base-metals coupled with a steady rise in pH. A good illustration of this seasonal shift or variation in mine water chemistry can be elicited from water data gathered at the portal entrance. Water sampled during the spring runoff (May) proved weakly acidic (pH 4.8) and contained dissolved concentrations of (in $\mu\text{g/L}$) 81.2 Cd, 5,780 Cu, and 14,900 Zn. In comparison, samples collected in July were characterized by a higher pH (5.8) and diminishing Cd (22 $\mu\text{g/L}$), Cu (907 $\mu\text{g/L}$), and Zn (5,440 $\mu\text{g/L}$) concentrations. By September, with the pH at neutral (7.0), the portal effluent only carried in solution (in $\mu\text{g/L}$) 8 Cd, 77 Cu, and 3,280 Zn (Dames & Moore, preliminary and unpublished data, 1998). More importantly, the collective mass of dissolved base-metals passing out of the portal (Cd, Cu, and Zn) declined by approximately 95 % between May and July, and another 74 % from July to

September. In contrast, seasonal attenuation of base-metals from the aqueous phase (chemical metal-partitioning) between the mine and Railroad Creek proceeds in a less predictable and consistent manner, typified by : (1) considerable loss of base-metals (Cd, Cu, and Zn) between the mine and Railroad Creek in the spring; (2) little or no depletion of base-metals along this passage in mid-summer; and (3) significant attenuation of Cu in the fall.

The incremental rise in pH that characterizes the portal discharge between May (pH 4.8) and September (pH 7.0) is significant and may have important environmental implications. Because the pH scale is simply an abbreviated computation (reflecting the activity or effective concentration of the free, uncomplexed hydrogen or hydronium ion) the true measure of this increase is somewhat diminished. By expressing pH in terms of molarity (moles per liter), however, the actual activity or concentration ($[H^+]$ by convention) of hydrogen ion in the May and September portal discharge can be established and a more realistic comparison made. Utilizing this approach, it was determined that the May discharge (1.6×10^{-5} mol/L H^+) was 160 times more acidic than the September portal drainage (1×10^{-7} mol/L H^+). This is particularly meaningful because the hydrogen ion activity or $[H^+]$ is considered a master variable in determining the composition of aqueous systems. For example, the increase in pH from spring to fall would produce a reciprocal decrease in the solubility of many dissolved species and accelerate metal-partitioning reactions (such as precipitation and sorption), both of which would substantially mitigate the dissolved metal load of the mine effluent.

Flocculent Material and Sorption Processes

Although an array of geochemical processes (such as inorganic and organic ion exchange and solution-gas interactions) may play a part in limiting the mobility and concentrations of dissolved metals in the Holden portal effluent, the formation and subsequent flocculation of metal-hydroxide minerals is the most obvious manifestation of metal partitioning and/or surface complexation from the aqueous phase. The ubiquitous flocculent material, which occurs as clotlike masses or loosely aggregated clusters of Al- and Fe hydroxides in the portal drainage, probably precipitated as a result of pH-dependent solubility reactions (Smith and others, 1989). The natural attenuating properties of hydrous-metal oxides is amply documented (Levinson, 1974; Rose and others, 1979; Smith and others, 1994) and their impact on the portal discharge and ultimately Railroad Creek cannot be minimized. In this regard, the portal water floc is not only instrumental in controlling aqueous Al and Fe concentrations, but also serves as an effective sink for many dissolved ionic species through coprecipitation and sorption reactions. Analysis of portal drainage floc collected by the USGS in the summer of 1995 clearly demonstrates these scavenging properties, with constituent base-metal concentrations as high as (in ppm) 1,100 Cu, 210 Pb, and 400 Zn (Kilburn and others, 1994). Although certain facets of the sorption process remain open to question, it is believed that the capacity of metal hydroxides to effectively scavenge dissolved metals is directly linked to the net surface charge of the hydroxide, which in turn is a function of pH. As a rule, metal hydroxides sustain a net positive charge in highly acidic solutions, and become progressively more negatively charged (by losing protons) as the pH approaches neutral values. Sorption of

cations therefore intensifies as pH increases, with bonding to solid phase hydroxides occurring over a narrow pH range (adsorption or pH edge) that is unique to individual metal species (Smith and Macalady, 1991). In addition to pH, other variables affecting this metal-partitioning reaction include the variety and abundance of metal hydroxide solids, the presence of competing ligands (such as dissolved organic carbon and sulfate), and the concentration and speciation of dissolved metals.

Interpretation and Discussion

The weathering of pyrite and other sulfides within the Holden mine is incessant, regardless of season. Oxygenated groundwater flowing along easily accessed conduits within the underground workings (e.g. shafts, drifts, and crosscuts) or as confined seepage in faults, fractures, and other permeable zones, aggressively oxidizes and dissolves pyrite and other sulfides, liberating Fe^{2+} , trace metals (such as Zn, Cu, and Cd) and high concentrations of acid (H^+) to the migrating waters. The ensuing solutions are corrosive and readily attack not only sulfides but the enclosing wallrock as well, prompting acid reactions with, and total or partial dissolution of the more resistate rock-forming (silicate) minerals (releasing into solution Al and the alkali and alkaline earth metals including Na, K, Ca, and Mg). In response to various acid-consuming processes such as the wallrock-acid reaction described above and/or dilution by transient mine and ground waters, the pH of the oxidizing solutions rises, resulting in the precipitation of Fe and Al hydroxides (possibly in concert with relatively insoluble sulfate phases such as anglesite) and sorption or coprecipitation of receptive trace metals (depending on pH). Because the hydrolysis of Fe^{3+} occurs at a much lower pH than Al, most of the dissolved Fe precipitates prior to passing through the adit portal and explains the relatively low aqueous concentrations of Fe and corresponding scarcity of Fe hydroxide material found in the surface portal effluent.

It is apparent that mine water chemistry at the Holden site is greatly affected by the seasonal availability of water. As mentioned previously, the lowest pH and highest dissolved metal concentrations (as well as total dissolved mass) are associated with the spring runoff. Although an excess of water in the spring certainly enhances oxidation processes, these complex reactions normally take place at rates much too slow to account for the rapidity at which added metal and acid loadings materialize in the spring portal discharge. The quick response (metal and acid loadings) to spring hydrologic conditions coupled with seasonal variation in Zn/Cu ratios (Alpers and others, 1994; Kilburn and Sutley, 1997) strongly suggest the dissolution and flushing of soluble metal salts. By-products of sulfide oxidation, metal salts or sulfates represent transitory storage of acid and metals in the solid phase, and their cycles of dissolution and precipitation is considered a primary influence on the seasonal fluctuations in mine water chemistry encountered at many pyrite-rich mining localities including other massive sulfide deposits such as Iron Mountain, California (Alpers, 1994) and genetically unrelated orebodies such as the Summitville, Colorado acid sulfate epithermal deposit (King, 1995). It is believed that these secondary minerals may accumulate in Holden's underground workings as saturated and supersaturated mine waters recede and evaporate during periods of dry weather (e.g. late summer and fall months at Holden). If this is the case, the highly soluble

efflorescent minerals would readily dissolve during the heavy spring runoff witnessed at Holden, resulting in the abrupt rise in dissolved metals and corresponding drop in pH that characterize the spring portal discharge. As water levels invariably ebb following the initial spring melt, acid and metal-loading would diminish as flushing subsides and sulfate precipitation commences in response to more temperate or arid conditions. This seasonal process of sulfate growth probably continues into the fall months or until reasonably steady flow conditions are achieved, at which time dissolved metal concentrations (in the portal drainage) stabilize and largely reflect direct sulfide oxidation. The salts would presumably remain intact until the next high-flow hydrologic event (probably the spring thaw). Fluctuations in this postulated hydrogeochemical cycle could result from summer storm events and abnormally mild weather conditions in winter.

Obviously, the rapid change in spring portal water chemistry is a multidimensional phenomenon and related to processes other than the simple dissolution of soluble secondary minerals. However, available data is of little help in defining these interactions, and the nature (and impact) of these controls remain largely conjectural. For instance, it is reasonable to assume (although evidence is lacking) that vestiges of the spring flushing event may persist in the mine in the form of isolated pools or ponds that develop in low-lying areas (unfilled stopes and drifts ?) or as saturated zones of interstitial water within the surrounding country rock, or both. During the low-flow, relatively dry period, the hypothesized seasonal reservoirs and pore solutions would become increasingly degraded as evaporation and prolonged contact with the adjacent country rock (and sulfides) concentrate and enhance acid and dissolved metal concentrations. These acidic, metalliferous solutions may then be flushed or swept out the portal as mine flooding commences the following spring.

At the time of the spring runoff (normally in May), the portal discharge is further characterized by a significant reduction in dissolved base-metal concentrations (Cd, Cu, and Zn) between the mine entrance and Railroad Creek. This coincides with an equally significant drop in the total dissolved mass of these constituents along the flow path. On the other hand, in July and September, base-metal concentrations remain reasonably constant along the length of the portal drainage despite experiencing a substantial decrease in total dissolved mass. It is believed that the collective metal depletion (mass and concentration) that accompanies the May discharge stems in large part from the diluting effects of the surrounding spring snowmelt together with sorption of dissolved metals (particularly Cu) onto solid phase oxyhydroxides. This presumption is based on field measurements, analytical data, and site-specific observations compiled by Dames & Moore and the USGS. During the May, 1997 field season, numerous rills, rivulets, and sheets of surface runoff that are not normally present in mid-summer and fall were observed entering the portal drainage at many localities between the mine entrance and Railroad Creek. This visual influx of presumably dilute surface water is consistent with field measurements taken by Dames & Moore, which indicate that the portal drainage increases in volume by about 23 % between the mine (flow rate of $2.63 \text{ ft}^3/\text{s}$) and the area just above the confluence with Railroad Creek (flow rate of $3.42 \text{ ft}^3/\text{s}$) (Dames and Moore, preliminary and unpublished data, 1998). In addition to dilution, sorption processes appear to play an active role in tempering dissolved base-metal levels (both concentration and mass). This metal partitioning reaction is most evident when

considering Cu, which declines about 60 % in concentration and 47 % in mass between the mine and Railroad Creek. This is not surprising, since Cu is preferentially sorbed by metal hydroxides within the limited pH range (4.8-4.9) of the spring portal drainage. Conversely, Zn and Cd are highly mobile, and would be expected to resist sorption at this pH, yet their total dissolved mass declines by 23 % and 16 %, respectively; suggesting some interaction and bonding with solid phase material. Regarding the mid-summer (July) and fall (September) portal effluent, water analysis outwardly reflects a rather conservative system (nonreacting), with dissolved base-metal concentrations remaining remarkably stable between the portal and Railroad Creek. This, however, is somewhat misleading. At this time of year, flow between the mine entrance and Railroad Creek is in a losing posture, (declining by roughly 26 % in July and 29 % in September), so that the total mass of dissolved base-metals entering Railroad Creek is actually much less than the dissolved load that initially exits the portal. Moreover, the dominant mode of mass reduction appears different in July than in September. In mid-summer (July), the total mass of dissolved Cu, Zn, and Cd declines about 27 %, 28 %, and 26 %, respectively. This compares favorably with the decrease in flow (26 %) between the portal (0.42 ft³/s) and Railroad Creek (0.31 ft³/s) and suggests the loss of metals along the flow path can largely be attributed to physical processes such as infiltration of portal water into underlying soil horizons, rather than chemical partitioning reactions. In contrast, mass balance calculations for the fall discharge (September) indicate that the total mass of dissolved Cu, Zn, and Cd decline along the flow path by roughly 74 %, 35 %, and 29 %, respectively. With measured flow rates between the portal (0.21 ft³/s) and Railroad Creek (0.15 ft³/s) dropping by only 29 %, a good portion of this mass reduction (especially Cu) is probably achieved via sorption onto various solids in contact with the portal discharge or suspended in the water column.

Mill Site, Waste Dumps, and Lagoon Area

Nowhere at the Holden site is visual evidence of spring runoff more conspicuous than the area above and generally west of Tailings Pile 1 (the western most tailings impoundment), where relatively heavy surface discharge from the mill is promptly channeled into a holding pond (lagoon area) below and west of the abandoned facility (figure 2). This seasonal outflow is in sharp contrast to mid-summer and fall levels, when mill effluent is generally limited to small seeps and trickles. Likewise, the holding pond (lagoon area) is largely dissipated by mid-summer and completely dry by autumn. The onset of high seasonal runoff is also marked by relatively heavy discharge associated with the waste rock piles located to the east and west of the mill facility (figure 2). By midsummer, however, surface runoff identified with the waste pile east of the mill is totally absent, while seepage linked with the western waste pile is greatly diminished (and virtually nonexistent by early autumn). According to Dames & Moore, the seasonal (spring) inundation of water that saturates the lower mill area and passes through the waste rock piles is largely derived from upgradient snowmelt that proceeds downslope as surface run-on and/or shallow groundwater in soil and reworked till units (a heterogeneous mixture of silty gravel, sand, and gravel)

Although intense sulfide weathering associated with residual ore material in the mill is ultimately responsible for much of the abandoned facility's acidic, metalliferous discharge, the flushing of soluble mineral salts is considered the immediate or primary control during the spring runoff and other episodes of seasonal precipitation. Chemical manifestations of this seasonal phenomenon can be rather striking as evidenced by the compositions of effluent sampled from within the recesses of the mill. These waters typically involve a complex suite of dissolved solids that are present in extremely high concentrations measured by the USGS of up to (in $\mu\text{g/L}$) 5.7 Ag, 760,000 Al, 4,800 Cd, 1,400 Co, 650,000 Cu, >500,000 Fe, >100,000 Mg, 1,100 Ni, 600 U, and 610,000 Zn (Kilburn and Sutley, 1996; Kilburn and Sutley, 1997). However, this discharge is generally in the form of small seeps or sulfate drippings that are inevitably diluted by the spring melt or evaporate during more arid conditions, leaving behind a metal-rich sulfate residue. Of more immediate concern is the base-metal rich water that actually exits the mill facility in the spring and early summer, either as channeled surface runoff (to the lagoon area) or as subsurface flows of indeterminate volume. The exodus of the metalliferous drainage from the mill (including the groundwater) is preceded by continuous mixing with more diffuse flows which attenuate the dissolved metal load, raise the pH, and promote the precipitation of Fe and Al hydroxides and sorption of responsive metal species (the lower levels of the mill are marked by thick accumulations of flocculated metal hydroxide material). The greatly tempered surface discharge may subsequently enter Railroad Creek via the lagoon, either as overland flow or low volume seepage. The flowpath of the corresponding groundwater is more uncertain. It is likely that as this subsurface water moves downward and laterally away from the mill area, it may emerge as Fe-poor, Cu-Zn-rich seepage along the banks of Railroad Creek and/or pass beneath the western periphery of Tailings Pile 1, mixing with and enhancing the base-metal content of Fe-rich tailings solutions. In the latter instance, the migrating waters may move upward in response to drying conditions and resultant capillary forces to evaporate on the surface, precipitating a host of secondary sulfate minerals (including Fe- Cu- and Zn- phases) that have been identified historically near the confluence of the Copper Creek diversion and Railroad Creek (Kilburn and others, 1994; Kilburn and others, 1995a,b).

The lagoon below the mill (figure 2) is a seasonal body of water characterized by an abundance of white-tan, metal hydroxide precipitates (probably Al) together with high levels of Cd, Cu, and Zn. This ephemeral holding pond (which is largely a spring and early summer entity) is fed by two discrete sources of weakly acidic, base-metal rich effluent, including: (1) the above referenced surface runoff from the mill; and (2) surface discharge and seepage springs associated with the large waste pile west of the mill structure (this surface discharge merges with the channeled mill flow prior entering the lagoon). Significant flow from these tributary effluents is by and large a spring and early summer occurrence, with fluctuations in the size or volume of the lagoon generally equated to their discharge (percolation and evaporation rates become more important as recharging events subside). As noted above, the lagoon may serve as a short-term reservoir for migrating, base-metal rich water known to enter Railroad Creek, either as seepage or small surface flows. Regarding the former, it is speculated that subsurface drainage from the lagoon may flow some distance down drainage before eventually surfacing as constituents of intermittent, Fe-rich seeps near the base of Tailings Pile 1. A potential artery for this

subsurface flow is the old Railroad Creek channel that underlies a portion the lagoon area. The channel, which was abandoned at the time Railroad Creek was diverted to the north (before the mine was operational), extends eastward from the lagoon and passes beneath the northern length of Tailings Pile 1 (Dames & Moore, preliminary and unpublished data, 1998).

The second waste rock pile is located approximately 100 m east of the abandoned mill, above the western half of Tailings Pile 1 (figure 2). During the spring thaw, weakly acidic, Fe-poor, base-metal rich effluent which surfaces near its base, flows west (about 70 m) along the break in slope, before being redirected and channeled across the western brim of Tailings Pile 1 and into Railroad Creek via the Copper Creek diversion. As the effluent, which has historically appeared milky-white owing to the precipitation of amorphous solids (probably Al-hydroxides; Kilburn and Sutley, 1997), advances downward toward Railroad Creek, base-metal concentrations are substantially moderated by natural physical (dilution) and chemical (precipitation and sorption) processes. Evidence of this attenuation is obvious when reviewing water quality data gathered by Dames & Moore in the spring (May) of 1997. Dissolved base-metal concentrations decrease from (in $\mu\text{g/L}$) 87.8 Cd, 7,880 Cu, and 11,200 Zn below the waste pile to (in $\mu\text{g/L}$) 50.1 Cd, 4,180 Cu, and 6,170 Zn near the juncture with the Copper Creek diversion. However, the total mass of dissolved base-metals increases dramatically (roughly 60 %) along this passage; a phenomenon which corresponds with an equally prominent gain in discharge volume (about 79 %) between the waste pile (flow rate of $2.0 \times 10^{-2} \text{ ft}^3/\text{s}$) and the Copper Creek diversion (flow rate of $9.47 \times 10^{-2} \text{ ft}^3/\text{s}$) (Dames & Moore, preliminary and unpublished data, 1998). Apparently this mutual increase in flow rate and total dissolved mass is largely dependent on numerous seeps and overland flows observed entering the drainage along the break in slope, above the tailings.

The cyclic retention and flushing of heavy metals from mine rock dumps is well chronicled from mine sites around the world (Lin and Herbert, 1997), and is no doubt the fundamental process contributing to the seasonal, base metal-rich discharge associated with the Holden waste piles. In general, the weathering of sulfides and other minerals in the leached zone of both waste dumps has resulted in the movement of metals downward to a zone of accumulation near the basement footing or in the underlying soils, where the metals are temporarily held in more stable secondary mineral phases. The resultant soluble minerals are likely candidates for dissolution and hydraulic flushing as upslope water infiltrates the waste piles during the course of the spring melt or episodic storm events, releasing base-metals and other elements to solution.

Honeymoon Heights drainage

The Honeymoon Heights area is located south and west of the mill facility, some 150 m in elevation above Railroad Creek (figure 2). This former prospect consists largely of exploratory pits and portals, scattered rock piles, and miscellaneous refuse customarily associated with historic mining operations. During the spring, the area is marked by intermittent, often coalescing small surface flows derived from upslope meteoric sources. Much of this seasonal surface runoff may experience some degree of metal loading from interaction with mineralized rock or its soluble by-products before discharging into

Railroad Creek as groundwater or intermittent seeps. One seep, which surfaces below Honeymoon Heights (figure 2), is of particular interest and represents a major, short-term, source of base-metals to Railroad Creek during the spring (the drainage is commonly dry for much of the year). Preliminary field and analytical data gathered by Dames & Moore indicate that as much as (in kg/day) 0.03 Cd, 5.0 Cu, and 4.0 Zn may enter Railroad Creek from this drainage during specific cycles of the spring runoff (Dames & Moore, preliminary and unpublished data, 1998). The origin of this metal-rich discharge, however, remains problematic. Perhaps, because of its location, the seep may simply be a seasonal manifestation of upgradient prospects in the Honeymoon Heights area. However, in order for the drainage to reach Railroad Creek along this flow path, it would of necessity, pass through or over roughly 150 m of shallow, moist mountain soil, where prevailing oxidizing and buffering conditions would be expected to reduce dissolved metal concentrations significantly. The relatively high Al and base-metal content of the waters would seem to preclude this passage and suggests a more local source, such as mineralized avalanche talus that may have accumulated in the lower reaches of the drainage (the flow path closely follows an avalanche track that can be traced through and above the Honeymoon Heights prospects) or even a breach in the underground workings of the mine itself.

East Area

The East Area is dominated by three massive tailings piles (numbered 1, 2, and 3 from west to east) that altogether encompass close to 90 acres east of the abandoned mill along the south bank of Railroad Creek (figure 2). Collectively, the piles contain about 7.7 million metric tons of tailings material capable of oxidizing at a rate estimated to be 200 times or more greater than undisturbed or unmined massive sulfide deposits (Boyle, 1994). Because this beneficiation refuse lies adjacent to Railroad Creek, the risk of disseminating both solid and liquid contaminants is greatly enhanced.

At the surface, the mill tailings are weathered a distinct yellow-ocher color and consist primarily of discarded gangue material (quartz, feldspar, and ferromagnesian silicates) and lesser amounts of secondary Fe-hydroxides (goethite) and hydroxysulfates (jarosite). The conspicuous absence of ore and ore-related minerals such as chalcopyrite and pyrite is not surprising, and is merely an indication of near surface oxidizing processes. Another manifestation of surface weathering, which may pique mining interests and facilitate remediation efforts, is the widespread enrichment of Au in the oxidized tailings (ranging from 0.43 to 1.7 ppm) (Kilburn and Sutley, 1996). As a result of site reclamation activities initiated and financed by the USFS (1989-1991), the tailings piles are currently capped by a veneer of granitic gravel to minimize persistent wind-blown contamination and a string of nurseries to propagate and restore native vegetation. In addition, the overall tailings impoundment was confined by an extensive network of basal riprap to guard against creek "undercutting" and forestall the gravitational sliding of unstable mill waste into Railroad Creek.

The East Area is further typified by the occurrence of acidic, Fe-rich seeps that surface intermittently near the base of the tailings. This seepage is invariably associated with substantial accumulations of ferric oxide precipitates, either as a thick coating on basal tailings material or as ferricrete conglomerates (a ferric oxide or hydroxide cemented

conglomerate composed of tailings material, gravel, and river rock) (Kilburn and Sutley, 1996). More importantly, the seeps and diffuse groundwater flow from beneath the tailings are considered the major source of total and dissolved Fe to Railroad Creek throughout the year (Dames and Moore, preliminary and unpublished data, 1998). Because of the low volume, intermittent nature of the tailings seeps, identification of many sites for seasonal resampling is difficult, if not impossible. Accordingly, flow rates and interdependent mass balance calculations were not considered for the following discussion. However, the collective water quality data compiled by Dames & Moore and the USGS appears sufficient to characterize the discharge and address potential seasonal controls. It is assumed (like elsewhere at Holden) that the total mass of dissolved solids is greatest during the spring runoff, and steadily declines as water levels progressively ebb in response to more arid conditions in the summer and fall months.

Fe-dominant Tailings Seepage

Nearly all of the acidic, Fe-dominant seeps emerging from tailings piles 1-3 surface adjacent to Railroad Creek, although some intermittent flows can be found along the eastern periphery of Tailings Pile 3. The tailings effluent is probably derived from a composite of surface water and groundwater sources that are part of a hydrologic regime much too complex to detail at length in this report. In brief, however, surface water can infiltrate the tailings as direct precipitation or as run-on from upgradient sources south of the tailings impoundment's. This surface water may eventually migrate downward to a zone of accumulation near the base of the tailings. Groundwater, also originating from upslope sources is believed to pass beneath the tailings through alluvium and reworked till units (Dames and Moore, preliminary and unpublished data, 1998). To what degree these discrete water sources interact is unknown, although some level of mixing is likely. Typical of the Holden site, penetration of surface water and groundwater into the tailings is highly seasonal, with the greatest influx generally associated with the spring runoff and episodic storm events. This cycle is reflected in the abundance and volume of tailings seepage, which are most prominent in the spring.

In general, the tailings seeps are acidic, Fe-rich, high-ionic strength (sum of cations and anions) solutions marked by a wide range in elemental compositions. During the lengthy 1997 field season (May to October), tailings seeps sampled by Dames & Moore contained dissolved metal levels ranging from (in $\mu\text{g/L}$) 3,920 - 115,000 Al, 1.8 - 40.3 Cd, 90 - 1,280 Cu, 8,670 - 1,260,000 Fe, and 232 - 5,700 Zn (Dames & Moore, preliminary and unpublished data, 1998) which is consistent with data compiled from earlier USGS investigations (Kilburn and Sutley, 1996, 1997; Kilburn and others, this report). Recognizing a seasonal bias in seepage chemistry, however, proved more difficult than first envisioned because of: (1) the transient nature of the discharge and the complicated flow patterns that accompany the spring melt; (2) the chemical and mineralogical heterogeneity of the tailings; and (3) the lack of definitive flow rate data. In any event, a perusal of the seepage data suggest that base-metal concentrations steadily diminish from spring to fall, whereas Fe and Al concentrations appear to increase from spring to mid-summer, then experience a decline by early fall. This seasonal variation in effluent chemistry can probably be traced, in large part, to the diluting and flushing effects of the

spring runoff. In addition, because the elemental suites of reference (Cu-Cd-Zn vs. Fe-Al) seemingly follow discrete seasonal trends, different sources of dissolved metals are suspected. Logical candidates include weathering primary minerals (both sulfide and silicate) and their soluble secondary by-products. Concerning the latter, the dissolution and hydraulic flushing of unstable secondary minerals is viewed as the overriding factor leading to the base-metal enrichment characteristic of the spring and early summer tailings discharge. Field and laboratory evidence strongly suggest that base-metals are derived not only from readily soluble material within the tailings, but also from upslope point sources such as the waste rock piles and the mill area (Kilburn and Sutley, 1996, 1997). Although some of this upslope water may infiltrate the tailings via surface run-on, the greater body of contaminated water probably enters the tailings as subsurface flows; i.e. the buried Railroad Creek channel. Following the initial spring runoff, the effects of flushing quickly diminish as the influx of extraneous, base-metal rich water abates and original mass of soluble minerals interspersed along the different flow paths is depleted. As a consequence, subsequent flows or short-term spikes of water through the tailings carry progressively lower dissolved base-metal concentrations. This pattern continues until stable flow conditions are attained in late fall or winter, when seepage compositions would be expected to remain fairly uniform until the next major flushing event (the following spring?). Regarding the Fe-Al suite, the oxidation of pyrite and resultant leaching of Al and other metals and elements (e.g., Mg, Na, and the rare earths) from largely silicate hosts within the tailings is a continuous process throughout the year, with weathering rates largely dependent on the seasonal availability of oxygenated groundwater and the height or position of the water table. Other parameters less (or not) subject to seasonal variability include the diffusion rate of atmospheric O₂ into the tailings, bacterial activity, sulfide and gangue mineralogy, mineral grain size, porosity and permeability, and the geometry and structural characteristics of the tailings (Boyle, 1994). During the spring inundation, however, dilution rather than direct oxidation appears to be the predominant process controlling dissolved Fe and Al concentrations, and the metals are probably attenuated by the heavy flow. As flooding subsides, these metal concentrations rise in accordance, augmented by additional Fe and Al loadings resulting from intensified pyrite oxidation and reciprocal silicate weathering (owing to the retention of excess water associated with the runoff event). As access to oxygenated groundwater becomes limited in late summer, pyrite oxidation and metal leaching diminish and Fe and Al concentrations decline proportionately until sustained base flow conditions resume in the fall, at which time seepage chemistry most likely stabilizes.

Clearly, water draining or in contact with the tailings provides an excellent avenue for hydrodynamic metals dispersion. However, the fundamental chemistry of the effluent remains somewhat puzzling. The primary controls for producing acidic, metal-rich drainage are clearly in place, with the mining and milling of massive sulfide ore affording oxygen-rich water easy access to tremendous volumes of fine-grained, pyrite rich tailings with little inherent acid-buffering capacity. Under these circumstances, the highly acidic, Fe-dominant tailings seepage identified by the USGS and Dames & Moore was not unexpected, and certainly compatible with a pyrite dominated system. However, the concentrations of accompanying base-metals, although relatively high by many standards, is a departure from the extreme levels frequently encountered elsewhere in waters derived

from weathering VMS mines and deposits. This may be related, in part, to yet unidentified processes such as the formation of local pH or redox boundaries (within the tailings) that can effectively restrict the mobility of dissolved metals (Blowes and others, 1991). A more likely scenario simply involves a lack of significant chalcopyrite and sphalerite in the tailings.

SUMMARY

Inactive or abandoned mine sites associated with volcanogenic massive sulfide deposits have yielded some of the most acidic, metalliferous mine drainage on record, and are of particular environmental concern. Accordingly, the U. S. Geological Survey conducted a series of geochemical surveys at the Holden mine, a relatively low-grade, Kuroko-type VMS deposit in order to assess the character, origin, and extent of contaminated waters derived from this former producer of base- and precious-metal ore. Seasonal variation in mine water chemistry were also addressed. Findings from these studies were augmented by compatible, but preliminary, water quality data collected at the mine by Dames & Moore on behalf of Alumet Inc. Collectively, these investigations (planned and administered independently) disclosed a dynamic and complex hydrologic regime, typified by a wide-range in mine effluent compositions that normally experience significant seasonal fluctuations in chemical composition and magnitude of flow. For simplicity, the mine discharge has been broadly categorized into two discrete groups based on chemical congruity and general proximity as follows: (1) acidic to strongly acidic, Fe-rich seeps that surface intermittently at or near the base of the tailings; and (2) weakly acidic to near neutral, base-metal rich (Cd, Cu, and Zn) water draining the mine, mine workings, and various waste piles and prospects located for the most part west of the tailings.

The elemental suites and concentrations (environmental signature) that characterize Holden's mine drainage is contingent on many natural controls and processes including (but not limited to) ore and gangue mineralogy, host rock lithology, geochemical interactions, and climate. These natural controls are enhanced and modified by certain anthropogenic factors which are largely a function of mineral development such as mining and ore processing methods. The mine discharge is further characterized by a marked seasonal variation in mine water chemistry. As a rule, the lowest pH and highest dissolved metal concentrations (and total dissolved mass) coincide with high flow conditions associated with the spring snowmelt. As conditions stabilize, and water flow increasingly subsides through the summer and fall, the pH levels gradually rise, whereas constituent dissolved metals decline perceptibly. This change in mine water chemistry is largely attributed to the dissolution and hydraulic flushing of soluble metal salts in the spring and their precipitation from saturated and supersaturated solutions in the summer and fall.

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Table 1. Analytical data for untreated water samples collected at the Holden mine, September 1996. Temperature, pH and conductivity are field measurements; anion analysis by ion chromatography

Sample #	Source	Temp C	pH	Conductivity uS/cm	Sulfate mg/L	Fluoride mg/L	Chloride mg/L
HM 700	RR Creek	7	6.23	49	12	<0.1	0.4
HM 702	Portal Effluent	8	6.22	797	400	0.4	8.3
HM 703	Portal Effluent	9	6.25	797	400	0.4	7.3
HM 704	Portal Effluent	9	6.52	797	400	0.5	7.2
HM 705	RR Creek	7	6.99	34	4	<0.1	0.4
HM 706	RR Creek	9	6.74	510	220	0.3	4.5
HM 707	RR Creek	7	6.86	33	4	<0.1	0.4
HM 708	RR Creek	7.5	6.81	53	10	<0.1	0.5
HM 709	RR Creek	7	6.93	36	4	<0.1	0.4
HM 710	Tailings Seep	6	3.28	5120	4730	3.6	12
HM 711	Tailings Seep	6	3.64	5200	4040	2.2	10
HM 712	Tailings Seep	6	2.97	4900	3900	3.9	5.8
HM 713	Tailings Seep	6	3.38	5060	4000	2.2	7.2
HM 714	Tailings Seep	6	3.44	5310	4530	2.1	8.3
HM 715	Tailings Seep	7	3.14	5790	4610	4.2	9.1
HM 716	RR Creek	5	5.45	364	66	<0.1	0.8
HM 717	Tailings Seep	5	3.46	3640	2000	1.4	3
HM 718	Tailings Seep	6	3.12	4190	2270	<0.1	2.4
HM 719	Tailings Seep	4	3.21	3280	1560	<0.1	4.8
HM 720	Tailings Seep	5	3.35	4630	2670	2.4	7.3
HM 721	Tailings Seep	5	3.45	3390	1610	<0.1	1.8
HM 722	RR Creek	5	6.11	58	16	<0.1	0.5
HM 723	Tailings Seep	5	3.27	4810	2980	1.5	4.3
HM 724	Tailings Seep	11	3.12	3060	1360	<0.1	2.7
HM 725	Tailings Seep	14	3.06	3110	1080	<0.1	1
HM 726	Tailings Seep	15	3.05	3140	1360	<0.1	5.3
HM 727	RR Creek	3	6.09	72	24	<0.1	0.4
HM 728	Tailings Seep	3	3.86	4640	2530	0.8	1.5
HM 729	Copper Creek	2	6.26	37	4	<0.1	0.1
HM 730	Copper Creek	2	6.39	37	4	<0.1	0.2

Table 2. ICP-AES analysis of filtered and acidified water samples collected at the Holden mine, Sept. 1976

Sample #	HM 700	HM 702	HM 703	HM 704	HM 705	HM 706	HM 707
Source	RR Creek	Portal Effluent	Portal Effluent	Portal Effluent	RR Creek	RR Creek	RR Creek
Al mg/L	0.018	0.044	0.043	0.034	0.013	0.023	0.011
B ug/L	13	250	250	240	16	170	16
Ba ug/L	5.4	10	11	11	5.2	8.7	5.1
Be ug/L	<10	<10	<10	<10	<10	<10	<10
Ca mg/L	7.3	160	160	150	6	110	5.8
Cd ug/L	<10	<10	<10	<10	<10	<10	<10
Co ug/L	<10	<10	<10	<10	<10	<10	<10
Cr ug/L	<10	<10	<10	<10	<10	<10	<10
Cu ug/L	<10	62	23	12	<10	11	<10
Fe mg/L	2.5	0.28	<0.1	<0.1	<0.1	<0.1	<0.1
K mg/L	<1	6.2	6.4	6.3	<1	4.4	<1
Li ug/L	<10	35	37	37	<10	24	<10
Mg mg/L	1	11	11	11	<1	7.7	<1
Mn ug/L	36	420	400	370	<10	270	<10
Mo ug/L	<20	<20	<20	<20	<20	<20	<20
Na mg/L	1.2	27	28	27	<1	18	<1
Ni ug/L	<10	<10	<10	<10	<10	<10	<10
P ug/L	<50	<50	<50	<50	<50	<50	<50
Pb ug/L	<50	<50	<50	<50	<50	<50	<50
Si mg/L	3.2	7.9	7.7	6.7	3.2	5.8	3
Sr ug/L	26	550	580	560	22	380	21
Ti ug/L	<50	<50	<50	<50	<50	<50	<50
V ug/L	<10	<10	<10	<10	<10	<10	<10
Zn ug/L	39	3600	3300	2900	<10	2200	<10
Sample #	HM 708	HM 709	HM 710	HM 711	HM 712	HM 713	HM 714
Source	RR Creek	RR Creek	Tailings Seep	Tailings Seep	Tailings Seep	Tailings Seep	Tailings Seep
Al mg/L	0.015	0.013	54	36	96	23	20
B ug/L	20	16	<10	<10	<10	<10	<10
Ba ug/L	5.2	5.1	5.4	11	<5	8.9	<5
Be ug/L	<10	<10	<10	<10	<10	<10	<10
Ca mg/L	8.5	6.2	300	260	250	340	340
Cd ug/L	<10	<10	50	26	21	23	34
Co ug/L	<10	<10	110	100	96	110	120
Cr ug/L	<10	<10	<10	<10	<10	<10	<10
Cu ug/L	<10	<10	<10	<10	180	<10	<10
Fe mg/L	<0.1	<0.1	1600	1500	1300	1400	1600
K mg/L	<1	<1	15	15	9.2	19	18
Li ug/L	<10	<10	48	38	110	41	38
Mg mg/L	<1	<1	180	150	140	200	210
Mn ug/L	<10	<10	13000	11000	9800	15000	16000
Mo ug/L	<20	<20	<20	<20	<20	<20	<20
Na mg/L	1.5	1.1	28	23	24	22	23
Ni ug/L	<10	<10	<10	<10	<10	10	11
P ug/L	<50	<50	<50	<50	<50	<50	<50
Pb ug/L	<50	<50	73	<50	<50	<50	<50
Si mg/L	3.2	3.1	26	19	44	24	24
Sr ug/L	31	23	750	680	610	770	800
Ti ug/L	<50	<50	<50	<50	<50	<50	<50
V ug/L	<10	<10	43	35	50	30	32
Zn ug/L	60	11	7800	5000	8300	6000	7300

Table 2. ICP-AES analysis of filtered and acidified water samples collected at the Holden mine, Sept. 1996

Sample #	HM 715	HM 716	HM 717	HM 718	HM 719	HM 720	HM 721
Source	Tailings Seep	RR Creek	Tailings Seep	Tailings Seep	Tailings Seep	Tailings Seep	Tailings Seep
Al mg/L	110	0.053	56	19	13	59	19
B ug/L	<10	<10	<10	<10	31	<10	<10
Ba ug/L	16	5.9	19	<5	5	7.1	20
Be ug/L	<10	<10	<10	<10	<10	<10	<10
Ca mg/L	470	16	380	410	350	390	330
Cd ug/L	43	<10	11	<10	<10	14	<10
Co ug/L	160	<10	33	35	29	78	34
Cr ug/L	<10	<10	<10	<10	<10	<10	<10
Cu ug/L	450	<10	1300	120	57	630	73
Fe mg/L	1500	43	290	430	230	740	290
K mg/L	26	1.2	23	28	27	28	27
Li ug/L	110	<10	58	45	52	81	33
Mg mg/L	270	4.7	100	130	100	140	92
Mn ug/L	19000	200	5000	6700	5200	8000	5000
Mo ug/L	<20	<20	<20	<20	<20	<20	<20
Na mg/L	37	1.7	16	18	16	19	14
Ni ug/L	54	<10	10	<10	<10	<10	<10
P ug/L	<50	<50	<50	<50	<50	<50	<50
Pb ug/L	56	<50	<50	<50	<50	<50	<50
Si mg/L	45	3.7	35	22	20	23	18
Sr ug/L	890	42	970	1200	940	890	850
Ti ug/L	<50	<50	<50	<50	<50	<50	<50
V ug/L	40	<10	<10	<10	<10	13	<10
Zn ug/L	8700	330	3700	1300	510	2400	760
Sample #	HM 722	HM 723	HM 724	HM 725	HM 726	HM 727	HM 728
Source	RR Creek	Tailings Seep	Tailings Seep	Tailings Seep	Tailings Seep	RR Creek	Tailings Seep
Al mg/L	0.036	88	17	12	11	0.04	51
B ug/L	12	<10	28	22	32	14	<10
Ba ug/L	5.5	11	28	32	48	6	41
Be ug/L	<10	<10	<10	<10	<10	<10	<10
Ca mg/L	8.7	300	310	330	300	10	310
Cd ug/L	<10	18	<10	<10	<10	<10	24
Co ug/L	<10	75	30	29	27	<10	73
Cr ug/L	<10	<10	<10	<10	<10	<10	<10
Cu ug/L	<10	110	280	210	150	<10	160
Fe mg/L	3.4	800	210	210	210	5	880
K mg/L	<1	32	28	27	28	<1	32
Li ug/L	<10	110	31	24	34	<10	34
Mg mg/L	1.3	130	74	74	73	1.7	100
Mn ug/L	40	9100	5200	5200	5200	66	7900
Mo ug/L	<20	<20	<20	<20	<20	<20	<20
Na mg/L	1	21	13	12	13	1.4	18
Ni ug/L	<10	<10	<10	<10	<10	<10	<10
P ug/L	<50	<50	<50	<50	<50	<50	<50
Pb ug/L	<50	<50	<50	<50	<50	<50	<50
Si mg/L	3.4	27	23	20	20	3.5	16
Sr ug/L	28	890	730	670	740	33	760
Ti ug/L	<50	<50	<50	<50	<50	<50	<50
V ug/L	<10	18	<10	<10	<10	<10	13
Zn ug/L	54	8000	950	780	960	55	4100

Table 2. ICP-AES analysis of filtered and acidified water samples collected at the Holden mine, Sept. 1996

Sample Source	HM 729 Copper Creek	HM 730 Copper Creek
Al mg/L	0.023	<0.01
B ug/L	<10	<10
Ba ug/L	6.7	6.5
Be ug/L	<10	<10
Ca mg/L	6	6
Cd ug/L	<10	<10
Co ug/L	<10	<10
Cr ug/L	<10	<10
Cu ug/L	<10	<10
Fe mg/L	<0.1	0.14
K mg/L	<1	<1
Li ug/L	<10	<10
Mg mg/L	<1	<1
Mn ug/L	<10	<10
Mo ug/L	<20	<20
Na mg/L	1.1	1.1
Ni ug/L	<10	<10
P ug/L	<50	<50
Pb ug/L	<50	<50
Si mg/L	3.8	3.7
Sr ug/L	20	20
Ti ug/L	<50	<50
V ug/L	<10	<10
Zn ug/L	<10	<10

Table 3. ICP-MS analysis of filtered and acidified water samples collected at the Holden mine, Sept. 1996
Elemental concentrations expressed as ug/L

Sample #	Source	Ag	As	Au	Ba	Be	Bi	Cd	Ce	Co	Cr	Cs	Cu	Dy	Er	Eu	Ga	Gd	Ge
HM 700	RR Creek	<0.05	<0.5	<0.1	1.3	<0.2	<0.05	0.1	<0.05	<0.5	<10	<0.05	1.6	<0.05	<0.05	<0.05	<0.5	<0.05	<0.2
HM 702	Portal Effluent	<0.05	<0.5	<0.1	4.6	<0.2	<0.05	5.3	0.3	1.3	<10	0.13	>20	<0.05	<0.05	<0.05	<0.5	<0.05	<0.2
HM 703	Portal Effluent	<0.05	<0.5	<0.1	4.6	<0.2	<0.05	5.3	0.1	1.4	<10	0.12	18	<0.05	<0.05	<0.05	<0.5	<0.05	<0.2
HM 704	Portal Effluent	<0.05	<0.5	<0.1	4.5	<0.2	<0.05	5.1	0.06	1.3	<10	0.13	11	<0.05	<0.05	<0.05	<0.5	<0.05	<0.2
HM 705	RR Creek	<0.05	0.5	<0.1	1.3	<0.2	<0.05	<0.1	<0.05	<0.5	<10	<0.05	1.4	<0.05	<0.05	<0.05	<0.5	<0.05	<0.2
HM 706	RR Creek	<0.05	<0.5	<0.1	3.4	<0.2	<0.05	3.8	0.05	1	<10	0.09	9.7	<0.05	<0.05	<0.05	<0.5	<0.05	<0.2
HM 707	RR Creek	<0.05	0.6	<0.1	0.91	<0.2	<0.05	<0.1	<0.05	<0.5	<10	<0.05	<0.5	<0.05	<0.05	<0.05	<0.5	<0.05	<0.2
HM 708	RR Creek	<0.05	0.6	<0.1	1.2	<0.2	<0.05	0.1	<0.05	<0.5	<10	<0.05	2	<0.05	<0.05	<0.05	<0.5	<0.05	<0.2
HM 709	RR Creek	<0.05	0.6	<0.1	1.1	<0.2	<0.05	<0.1	<0.05	<0.5	<10	<0.05	1	<0.05	<0.05	<0.05	<0.5	<0.05	<0.2
HM 710	Tailings Seep	<0.05	<0.5	<0.1	2.5	0.9	<0.05	>20	74	18	<10	0.32	>20	9.2	4.8	2.7	0.5	10	0.3
HM 711	Tailings Seep	<0.05	1.7	<0.1	6.2	0.7	<0.05	4.7	55	16	<10	0.28	>20	6.3	3.2	1.6	<0.5	6.3	0.3
HM 712	Tailings Seep	<0.05	1	<0.1	1.6	1.3	<0.05	2.8	55	>20	20	0.37	>20	7.6	3.9	2.3	0.7	8.3	0.2
HM 713	Tailings Seep	<0.05	0.8	<0.1	4.9	0.2	<0.05	1.7	20	>20	<10	0.37	>20	2.2	1.2	0.58	0.6	2.3	0.2
HM 714	Tailings Seep	<0.05	<0.5	<0.1	<0.05	0.4	<0.05	11	21	>20	<10	0.34	>20	2.5	1.4	0.72	<0.5	2.7	0.3
HM 715	Tailings Seep	<0.05	1.7	<0.1	10	1.2	<0.05	14	85	>20	<10	0.49	>20	13	6.7	3.4	0.6	13	0.3
HM 716	RR Creek	<0.05	<0.5	<0.1	1.8	<0.2	<0.05	0.9	0.42	1.2	<10	<0.05	4.7	<0.05	<0.05	<0.05	<0.5	0.05	<0.2
HM 717	Tailings Seep	<0.05	3.6	<0.1	11	0.7	<0.05	7.4	38	11	<10	0.14	>20	6.3	3.3	1.6	<0.5	6.4	<0.2
HM 718	Tailings Seep	<0.05	<0.5	<0.1	<0.05	0.2	<0.05	1.3	12	9.2	<10	0.16	>20	2	1	0.71	<0.5	2.4	<0.2
HM 719	Tailings Seep	<0.05	<0.5	<0.1	1.6	0.3	<0.05	0.9	11	12	<10	0.12	>20	1.8	0.81	0.47	<0.5	1.8	<0.2
HM 720	Tailings Seep	<0.05	<0.5	<0.1	4.2	1	<0.05	5.5	55	18	<10	0.11	>20	7.2	3.6	1.9	<0.5	7.9	<0.2
HM 721	Tailings Seep	<0.05	<0.5	<0.1	13	0.4	<0.05	1.8	37	13	<10	<0.05	>20	3.5	1.8	0.84	<0.5	4	<0.2
HM 722	RR Creek	<0.05	<0.5	<0.1	1.7	<0.2	<0.05	0.2	0.06	<0.5	<10	<0.05	1.5	<0.05	<0.05	<0.05	<0.5	<0.05	<0.2
HM 723	Tailings Seep	<0.05	<0.5	<0.1	5.5	1.4	<0.05	4.6	57	>20	<10	0.23	>20	6	3.2	1.4	<0.5	6.5	<0.2
HM 724	Tailings Seep	<0.05	<0.5	<0.1	16	0.3	<0.05	4.9	23	15	<10	0.12	>20	2.8	1.5	0.66	<0.5	3	<0.2
HM 725	Tailings Seep	<0.05	<0.5	<0.1	>20	0.3	<0.05	4	16	15	<10	0.1	>20	2	1	0.46	<0.5	2.2	<0.2
HM 726	Tailings Seep	<0.05	<0.5	<0.1	>20	0.2	<0.05	2	10	13	<10	0.12	>20	1.4	0.74	0.32	<0.5	1.6	<0.2
HM 727	RR Creek	<0.05	<0.5	<0.1	1.7	<0.2	<0.05	0.2	0.08	<0.5	<10	<0.05	1.9	<0.05	<0.05	<0.05	<0.5	<0.05	<0.2
HM 728	Tailings Seep	<0.05	<0.5	<0.1	>20	0.7	<0.05	9.7	28	>20	<10	0.07	>20	4.4	2.2	1.2	<0.5	4.5	<0.2
HM 729	Copper Creek	<0.05	<0.5	<0.1	2.4	<0.2	<0.05	<0.1	<0.05	<0.5	<10	<0.05	<0.5	<0.05	<0.05	<0.05	<0.5	<0.05	<0.2
HM 730	Copper Creek	<0.05	<0.5	<0.1	2	<0.2	<0.05	<0.1	<0.05	<0.5	<10	<0.05	<0.5	<0.05	<0.05	<0.05	<0.5	<0.05	<0.2

Table 3. ICP-MS analysis of filtered and acidified water samples collected at the Holden mine, Sept. 1996 (cont)
Elemental concentrations expressed as ug/L

Sample #	Source	Hf	Ho	In	La	Li	Mg	Mo	Nb	Nd	Ni	Pb	Pr	Rb	Sb	Sm	Sn	Sr	Ta
HM 700	RR Creek	<0.05	<0.05	<0.05	<0.05	0.3	730	0.5	<0.1	<0.05	<1	<0.05	<0.05	0.6	0.06	<0.05	<1	>20	<0.05
HM 702	Portal Effluent	<0.05	<0.05	<0.05	0.18	>20	>1000	1	<0.1	0.17	<1	0.17	<0.05	6.2	<0.05	<0.05	<1	>20	<0.05
HM 703	Portal Effluent	<0.05	<0.05	<0.05	0.1	>20	>1000	1	<0.1	0.05	<1	<0.05	<0.05	6.2	<0.05	<0.05	<1	>20	<0.05
HM 704	Portal Effluent	<0.05	<0.05	<0.05	0.05	>20	>1000	1.1	<0.1	<0.05	<1	<0.05	<0.05	6.1	<0.05	<0.05	<1	>20	<0.05
HM 705	RR Creek	<0.05	<0.05	<0.05	<0.05	<0.3	390	0.6	<0.1	<0.05	<1	<0.05	<0.05	0.5	0.06	<0.05	<1	18	<0.05
HM 706	RR Creek	<0.05	<0.05	<0.05	<0.05	19	>1000	0.9	<0.1	<0.05	<1	<0.05	<0.05	4.6	<0.05	<0.05	<1	>20	<0.05
HM 707	RR Creek	<0.05	<0.05	<0.05	<0.05	0.4	380	0.6	<0.1	<0.05	<1	<0.05	<0.05	0.5	0.05	<0.05	<1	17	<0.05
HM 708	RR Creek	<0.05	<0.05	<0.05	<0.05	0.7	540	0.6	<0.1	<0.05	<1	<0.05	<0.05	0.6	0.06	<0.05	<1	>20	<0.05
HM 709	RR Creek	<0.05	<0.05	<0.05	<0.05	<0.3	420	0.6	<0.1	<0.05	<1	<0.05	<0.05	0.5	0.05	<0.05	<1	18	<0.05
HM 710	Tailings Seep	<0.05	1.8	0.28	33	>20	>1000	0.1	0.1	36	>20	0.33	8.9	30	0.08	7.9	<1	>20	0.16
HM 711	Tailings Seep	<0.05	1.2	0.08	27	>20	>1000	0.1	<0.1	22	>20	0.46	5.9	33	<0.05	4.5	<1	>20	<0.05
HM 712	Tailings Seep	<0.05	1.4	1.1	24	>20	>1000	<0.1	<0.1	30	19	2.6	7.2	38	<0.05	7.5	<1	>20	<0.05
HM 713	Tailings Seep	<0.05	0.42	0.15	12	>20	>1000	<0.1	<0.1	9.3	>20	<0.05	2.3	30	<0.05	2.2	<1	>20	<0.05
HM 714	Tailings Seep	<0.05	0.49	0.11	13	>20	>1000	<0.1	<0.1	10	>20	0.13	2.5	30	<0.05	2.4	<1	>20	<0.05
HM 715	Tailings Seep	<0.05	0.24	0.13	42	>20	>1000	0.2	<0.1	43	>20	3.2	11	37	<0.05	10	<1	>20	<0.05
HM 716	RR Creek	0.09	<0.05	<0.05	0.29	0.8	>1000	0.5	<0.1	0.18	2	<0.05	<0.05	1	0.12	<0.05	<1	>20	0.13
HM 717	Tailings Seep	0.08	1.2	0.05	15	>20	>1000	0.1	<0.1	22	11	1.4	5	16	0.11	5.8	<1	>20	0.73
HM 718	Tailings Seep	<0.05	0.36	<0.05	4.7	>20	>1000	<0.1	<0.1	9	7	0.53	1.9	13	<0.05	2.5	<1	>20	0.22
HM 719	Tailings Seep	<0.05	0.3	<0.05	4.8	>20	>1000	<0.1	<0.1	6.7	7	0.36	1.6	11	<0.05	1.7	<1	>20	0.09
HM 720	Tailings Seep	<0.05	1.3	0.06	21	>20	>1000	0.1	<0.1	28	12	1.1	6.5	21	<0.05	7.3	<1	>20	0.09
HM 721	Tailings Seep	<0.05	0.64	<0.05	14	>20	>1000	<0.1	<0.1	17	7	5.7	4	15	<0.05	4.2	<1	>20	<0.05
HM 722	RR Creek	<0.05	<0.05	<0.05	<0.05	0.6	890	0.6	<0.1	<0.05	<1	<0.05	<0.05	0.6	<0.05	<0.05	<1	>20	<0.05
HM 723	Tailings Seep	<0.05	1.2	0.13	26	>20	>1000	<0.1	<0.1	25	18	2.7	6.3	28	<0.05	5.7	<1	>20	<0.05
HM 724	Tailings Seep	<0.05	0.53	0.1	7.7	>20	>1000	<0.1	<0.1	11	10	2.5	2.4	14	<0.05	2.9	<1	>20	<0.05
HM 725	Tailings Seep	<0.05	0.38	0.06	5.6	18	>1000	<0.1	<0.1	7.4	9	2	1.7	13	<0.05	2	<1	>20	<0.05
HM 726	Tailings Seep	<0.05	0.27	<0.05	4.2	>20	>1000	<0.1	<0.1	5.6	9	1.4	1.3	14	<0.05	1.5	<1	>20	<0.05
HM 727	RR Creek	<0.05	<0.05	<0.05	0.05	0.6	>1000	0.5	<0.1	<0.05	<1	<0.05	<0.05	0.6	<0.05	<0.05	<1	>20	<0.05
HM 728	Tailings Seep	<0.05	0.82	<0.05	12	>20	>1000	<0.1	<0.1	14	12	0.22	3.4	14	<0.05	3.7	<1	>20	<0.05
HM 729	Copper Creek	<0.05	<0.05	<0.05	<0.05	<0.3	510	0.5	<0.1	<0.05	<1	<0.05	<0.05	0.5	<0.05	<0.05	<1	16	<0.05
HM 730	Copper Creek	<0.05	<0.05	<0.05	<0.05	<0.3	510	0.5	<0.1	<0.05	<1	<0.05	<0.05	0.5	<0.05	<0.05	<1	16	<0.05

Table 3. ICP-MS analysis of filtered and acidified water samples collected at the Holden mine, Sept. 1996 (cont)
Elemental concentrations expressed as ug/L

Sample #	Source	Tb	Te	Th	Tl	Tm	U	V	W	Y	Yb	Zn	Zr
HM 700	RR Creek	<0.05	<0.5	<0.05	<0.1	<0.05	0.02	<10	<0.05	<0.1	<0.05	>20	<0.1
HM 702	Portal Effluent	<0.05	<0.5	<0.05	<0.1	<0.05	0.28	<10	0.09	0.4	<0.05	>20	<0.1
HM 703	Portal Effluent	<0.05	<0.5	<0.05	<0.1	<0.05	0.28	<10	0.12	0.1	<0.05	>20	<0.1
HM 704	Portal Effluent	<0.05	<0.5	<0.05	<0.1	<0.05	0.2	<10	0.1	<0.1	<0.05	>20	<0.1
HM 705	RR Creek	<0.05	<0.5	<0.05	<0.1	<0.05	0.02	<10	<0.05	<0.1	<0.05	2.8	<0.1
HM 706	RR Creek	<0.05	<0.5	<0.05	<0.1	<0.05	0.06	<10	0.09	<0.1	<0.05	>20	<0.1
HM 707	RR Creek	<0.05	<0.5	<0.05	<0.1	<0.05	0.02	<10	<0.05	<0.1	<0.05	0.8	<0.1
HM 708	RR Creek	<0.05	<0.5	<0.05	<0.1	<0.05	0.03	<10	<0.05	<0.1	<0.05	>20	<0.1
HM 709	RR Creek	<0.05	<0.5	<0.05	<0.1	<0.05	0.02	<10	<0.05	<0.1	<0.05	5.7	<0.1
HM 710	Tailings Seep	1.6	<0.5	1.2	<0.1	0.52	3.3	10	<0.05	77	2.7	>20	0.2
HM 711	Tailings Seep	1	<0.5	0.93	<0.1	0.35	1.6	<10	<0.05	62	1.8	>20	<0.1
HM 712	Tailings Seep	1.3	<0.5	3.2	<0.1	0.49	7.4	>20	<0.05	51	2.9	>20	0.5
HM 713	Tailings Seep	0.37	<0.5	0.9	<0.1	0.15	1.2	<10	<0.05	18	0.85	>20	0.2
HM 714	Tailings Seep	0.43	<0.5	0.88	<0.1	0.16	1.4	<10	<0.05	22	1	>20	0.1
HM 715	Tailings Seep	2.1	<0.5	0.94	<0.1	0.82	8.3	20	<0.05	96	4.6	>20	1
HM 716	RR Creek	<0.05	<0.5	<0.05	<0.1	<0.05	0.03	<10	<0.05	0.5	<0.05	>20	<0.1
HM 717	Tailings Seep	1.1	<0.5	0.42	<0.1	0.42	7.5	<10	<0.05	35	2.5	>20	0.2
HM 718	Tailings Seep	0.37	<0.5	0.88	<0.1	0.14	1.7	<10	<0.05	9.6	0.92	>20	<0.1
HM 719	Tailings Seep	0.28	<0.5	0.4	<0.1	0.12	1	<10	<0.05	9.1	0.64	>20	<0.1
HM 720	Tailings Seep	1.3	<0.5	2.1	<0.1	0.46	5.7	<10	<0.05	41	2.6	>20	0.1
HM 721	Tailings Seep	0.63	<0.5	2.3	<0.1	0.24	2.1	<10	<0.05	19	1.3	>20	<0.1
HM 722	RR Creek	<0.05	<0.5	<0.05	<0.1	<0.05	<0.02	<10	<0.05	<0.1	<0.05	>20	<0.1
HM 723	Tailings Seep	1.1	<0.5	3.2	<0.1	0.38	3.9	<10	<0.05	46	2.1	>20	0.2
HM 724	Tailings Seep	0.5	<0.5	1	<0.1	0.21	4.9	<10	<0.05	16	1.2	>20	<0.1
HM 725	Tailings Seep	0.36	<0.5	0.56	<0.1	0.14	3.5	<10	<0.05	11	0.86	>20	0.5
HM 726	Tailings Seep	0.25	<0.5	0.64	<0.1	0.1	2.1	<10	<0.05	7.5	0.61	>20	<0.1
HM 727	RR Creek	<0.05	<0.5	<0.05	<0.1	<0.05	<0.02	<10	<0.05	<0.1	<0.05	>20	<0.1
HM 728	Tailings Seep	0.75	<0.5	0.06	<0.1	0.27	4	<10	<0.05	29	1.6	>20	<0.1
HM 729	Copper Creek	<0.05	<0.5	<0.05	<0.1	<0.05	<0.02	<10	<0.05	<0.1	<0.05	<0.5	<0.1
HM 730	Copper Creek	<0.05	<0.5	<0.05	<0.1	<0.05	<0.02	<10	<0.05	<0.1	<0.05	<0.5	<0.1

Table 4. Secondary sulfate minerals identified at the base of the Holden mill tailings, July 1994.

<u>MINERAL</u>	<u>FORMULA</u>
Pickeringite	$\text{MgAl}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$
Hexahydrite	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$
Alunogen	$\text{Al}_2(\text{SO}_4)_3 \cdot 17\text{H}_2\text{O}$
Halotrichite	$\text{Fe}^{\text{II}}\text{Al}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$
Siderotil	$\text{Fe}^{\text{II}}\text{SO}_4 \cdot 5\text{H}_2\text{O}$
Melanterite	$\text{Fe}^{\text{II}}\text{SO}_4 \cdot 7\text{H}_2\text{O}$
Rozenite	$\text{Fe}^{\text{II}}\text{SO}_4 \cdot 4\text{H}_2\text{O}$
Romerite	$\text{Fe}^{\text{II}}\text{Fe}^{\text{III}}(\text{SO}_4)_4 \cdot 14\text{H}_2\text{O}$
Jarosite	$\text{KFe}_3^{\text{III}}(\text{SO}_4)_2(\text{OH})_6$
Antlerite	$\text{Cu}_3(\text{SO}_4)(\text{OH})_4$
Chalcanthite	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$
Bonattite	$\text{CuSO}_4 \cdot 3\text{H}_2\text{O}$
Dietrichite	$(\text{Zn}, \text{Fe}^{\text{II}}, \text{Mn})\text{Al}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$
Gunningite	$(\text{Zn}, \text{Mn})\text{SO}_4 \cdot \text{H}_2\text{O}$
Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

Table 5. Secondary sulfate minerals identified in the abandoned Holden mill, July 1995.

<u>MINERAL</u>	<u>FORMULA</u>
Starkeyite	$\text{MgSO}_4 \cdot 4\text{H}_2\text{O}$
Alunogen	$\text{Al}_2(\text{SO}_4)_3 \cdot 17\text{H}_2\text{O}$
Siderotil	$\text{Fe}^{\text{II}}\text{SO}_4 \cdot 5\text{H}_2\text{O}$
Rozenite	$\text{Fe}^{\text{II}}\text{SO}_4 \cdot 4\text{H}_2\text{O}$
Bilinite	$\text{Fe}^{\text{II}}\text{Fe}^{\text{III}}(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$
Hyronium Jarosite	$(\text{H}_3\text{O})\text{Fe}_3^{\text{III}}(\text{SO}_4)_2(\text{OH})_6$
Natrojarosite	$\text{NaFe}^{\text{III}}(\text{SO}_4)_2(\text{OH})_6$
Ammoniojarosite	$(\text{NH}_4)\text{Fe}_3^{\text{III}}(\text{SO}_4)_2(\text{OH})_6$
Butlerite	$\text{Fe}^{\text{III}}(\text{SO}_4)(\text{OH}) \cdot 2\text{H}_2\text{O}$
Xitieshanite	$\text{Fe}^{\text{III}}(\text{SO}_4)(\text{OH}) \cdot 7\text{H}_2\text{O}$
Antlerite	$\text{Cu}_3(\text{SO}_4)(\text{OH})_4$
Chalcanthite	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$
Bonattite	$\text{CuSO}_4 \cdot 3\text{H}_2\text{O}$
Gunningite	$(\text{Zn}, \text{Mn})\text{SO}_4 \cdot \text{H}_2\text{O}$

Table 6. Secondary sulfate minerals identified in the abandoned Holden mill, May 1996.

<u>MINERAL</u>	<u>FORMULA</u>
Pickeringite	$\text{MgAl}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$
Epsomite	$\text{MgSO}_4 \cdot 7\text{H}_2\text{O}$
Hexahydrite	$\text{MgSO}_4 \cdot 6\text{H}_2\text{O}$
Halotrichite	$\text{Fe}^{\text{II}}\text{Al}_2(\text{SO}_4)_4 \cdot 22\text{H}_2\text{O}$
Siderotil	$\text{Fe}^{\text{II}}\text{SO}_4 \cdot 5\text{H}_2\text{O}$
Melanterite	$\text{Fe}^{\text{II}}\text{SO}_4 \cdot 7\text{H}_2\text{O}$
Rozenite	$\text{Fe}^{\text{II}}\text{SO}_4 \cdot 4\text{H}_2\text{O}$
Romerite	$\text{Fe}^{\text{II}}\text{Fe}^{\text{III}}(\text{SO}_4)_4 \cdot 14\text{H}_2\text{O}$
Chalcanthite	$\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$
Antlerite	$\text{Cu}_3(\text{SO}_4)(\text{OH})_4$
Goslarite	$\text{ZnSO}_4 \cdot 7\text{H}_2\text{O}$
Bianchite	$(\text{Zn}, \text{Fe}^{\text{II}})\text{SO}_4 \cdot 6\text{H}_2\text{O}$
Gypsum	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$

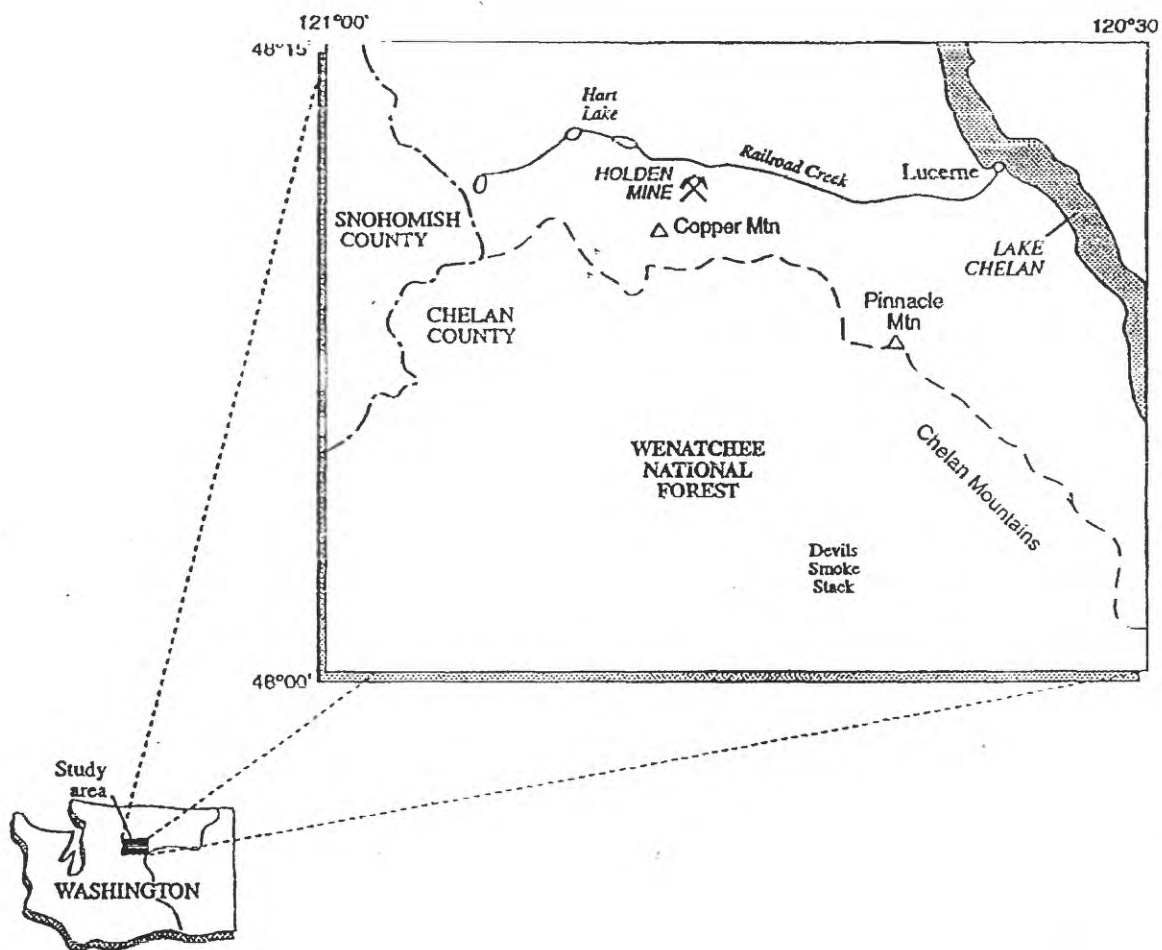


Figure 1. Location of the Holden Mine, Chelan County, Washington

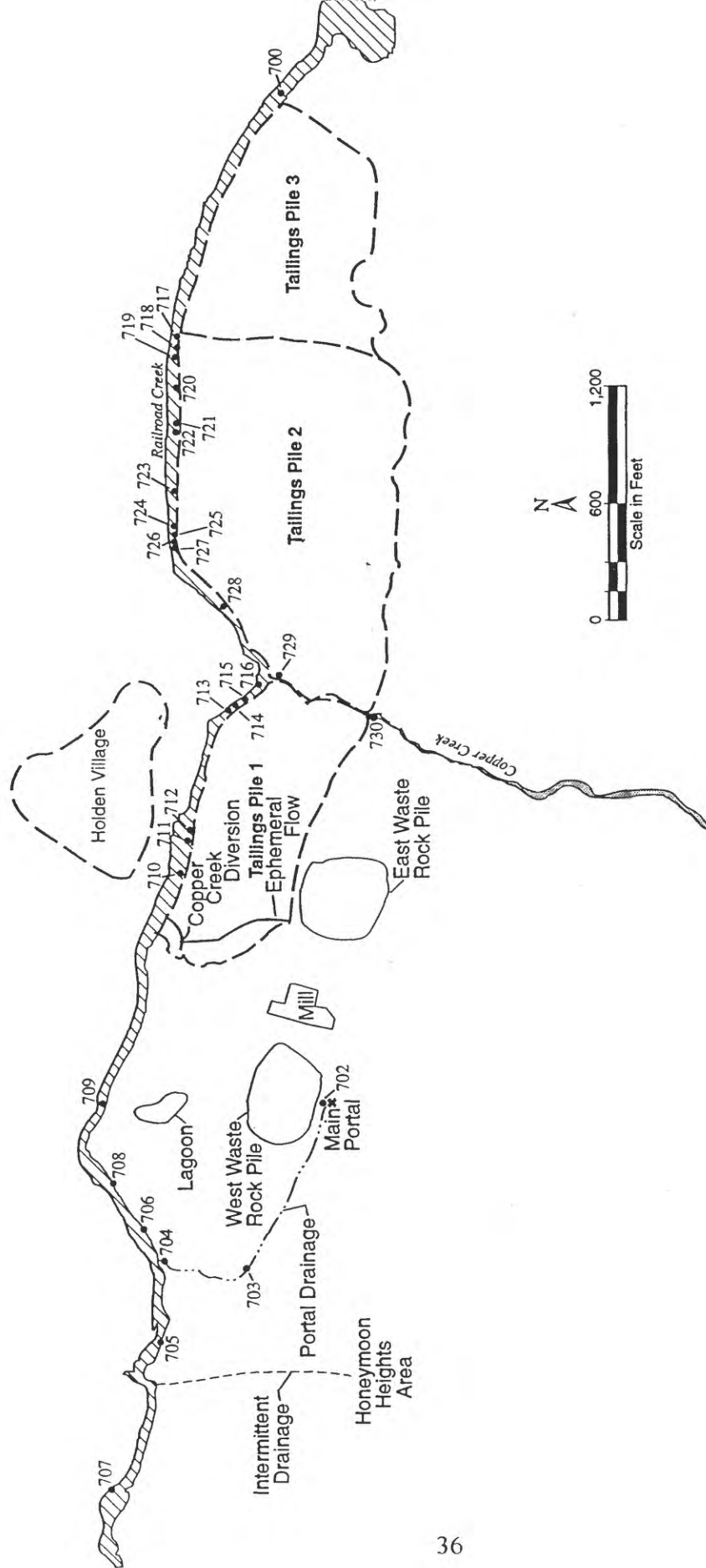


Figure 2. Holden mine site map showing the location of water samples collected in September 1996