

Environmental-Geochemical Study of the Slate Creek Antimony Deposit, Kantishna Hills, Denali National Park and Preserve, Alaska

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Abstract

We undertook a reconnaissance environmental-geochemical investigation in 1998 at the Slate Creek antimony deposit in Denali National Park and Preserve, Alaska. This cooperative study between the U.S. Geological Survey and the National Park Service focused on identifying and characterizing environmental geochemical signatures associated with this historical mining area. The deposit, which is hosted by quartzite, quartz-mica schist, marble, and greenstone, is a locally brecciated fissure quartz vein system containing stibnite and lesser pyrite, stibiconite, kermesite, boulangerite, cervantite, and arsenopyrite. About 800,000 lb (362,400 kg) of Sb was produced from 1905 through 1983.

Samples collected include water, stream-sediment, rock, and soil samples from 13 sites upstream of, downstream from, and at the mineralized area. Stream-water samples collected outside the disturbed mining area were bicarbonate dominant and had near-neutral pH values, conductivities ranging from 130 to 300 $\mu\text{S}/\text{cm}$, alkalinities ranging from 60 to 130 mg/L, and total-dissolved-solids (TDS) contents of as much as 316 mg/L. Two samples of naturally mineralized spring water collected outside the disturbed mining area had pH values of 5.6 and 7.7, conductivities of 300 and 750 $\mu\text{S}/\text{cm}$, alkalinities of 57 and 180 mg/L, and TDS contents of 230 and 544 mg/L. One of the springs was sulfate dominant, and the other mixed sulfate-bicarbonate dominant. Surface waters draining the minesite proper were sulfate dominant and had pH values ranging from 2.7 to 5.8, conductivities ranging from 770 to 1,700 $\mu\text{S}/\text{cm}$, alkalinities ranging from 0 to 110 mg/L, and TDS contents ranging from 671 to 993 mg/L. Stream waters from Slate Creek below the mine and mineralized area were mixed sulfate-bicarbonate dominant and had near-neutral pH values, conductivities ranging from 260 to 280 $\mu\text{S}/\text{cm}$, alkalinities ranging from 63 to 78 mg/L, and TDS contents of less than 250 mg/L. Metallic-ion concentrations in stream waters all steadily decreased with distance from the deposit. Parameters measured in waters draining the minesite that exceeded established Alaska drinking-water standards include pH value and SO_4^{2-} , As, Fe, Mn, Ni, Sb, and

TDS contents. Waters in Slate Creek immediately below the mine exceed drinking-water standards for As, Fe, Mn, and Sb contents. At the mouth of Slate Creek, about 1.8 mi (2.9 km) downstream from the mine, only Mn and Sb contents exceed drinking-water standards. Interestingly, stream- and spring-water samples collected from areas unaffected by the minesite also exceed drinking-water standards for pH value and SO_4^{2-} , As, Fe, Mn, Sb, and TDS contents. Aquatic-life standards are exceeded only by minesite waters for As, Cd, Cu, Ni, and Zn contents.

Elements measured in highly anomalous concentrations in stream-sediment, rock, and soil samples collected outside the minesite include As, Mn, and Sb. Mine waste and mineralized outcrops at the minesite have highly anomalous As and Sb contents. Stream-sediment samples downstream from the mineralized area have highly anomalous As, Mn, and Sb contents.

The low pH value and predominance of sulfate in mine-related waters are due largely to the dissolution of pyrite. Stream waters downstream from the minesite have major-anion compositions that reflect mixing of bicarbonate-dominant, near-neutral pH waters with mineralized, acidic, sulfate-dominant waters. Metallic ions abundant in the mine-related waters are quickly coprecipitated with Fe oxide flocs upon mixing with bicarbonate waters, resulting in heavily Fe oxide-stained alluvium downstream from the deposit. Ionic species in high concentrations that remain mobile at higher pH values, such as Mn, Sb, SO_4^{2-} , and Zn, remain in solution downstream.

The presence of natural springs within the mineralized area but outside the disturbed mining area suggests premining spring waters that naturally ranged from acidic to neutral in pH value, had relatively high conductivities and varying high TDS contents, were Fe rich, and were metalliferous. Red-stained alluvial gravel along Slate Creek, natural Fe oxide-rich springs near the head of the Slate Creek basin, and ferricrete deposits probably were present before, and aided prospectors in, the discovery of the Slate Creek antimony deposit. However, the naturally degraded waters that were likely present, as well as the extent of iron staining along Slate Creek, have certainly both been worsened by historical mining activities.

Introduction

We undertook a reconnaissance environmental-geochemical investigation in the Slate Creek drainage of Denali National Park and Preserve in 1998. Surface-water, bedload-stream-sediment, rock, and mine-waste samples were collected from the Slate Creek antimony deposit near the head of the drainage and at intervals downstream along Slate Creek to its confluence with Eldorado Creek, about 1.8 mi (2.9 km) downstream. Historically, the Slate Creek antimony deposit has also been referred to as the “Antimony” or “Taylor mine” (Capps, 1918; Cobb, 1972; Dames & Moore, 1992). The purpose of this cooperative study with the National Park Service (NPS) was to characterize the geochemistry of the mineralized area, to identify potential environmental-geochemical hazards, and to determine baseline levels for selected elements. The focus of this report is on the hydrogeochemical media, the principal avenue for movement of metals from rocks and sediment into the aquatic biota.

The fieldwork was conducted over a 1-week period from August 9 to 15, 1998. Summer 1998 was an unusually wet period, with numerous rainstorms occurring throughout park during the season (Ken Karle, oral commun., 1998). As a result, springs issued from numerous points in and around the Slate Creek antimony deposit, and surface flow was observed in all intermittent drainages.

The Slate Creek antimony deposit is located in the northwestern part of Denali National Park and Preserve, about 5 mi (8 km) southwest of Kantishna and about 6 mi (10 km) due west of Wonder Lake (fig. 1). Low, rolling, heavily vegetated hills typify the topography of the Kantishna Hills in the vicinity of the Slate Creek antimony deposit (fig. 2A). Elevations range from about 2,100 ft (640 m), at the confluence of Slate and Eldorado Creeks, to 3,774 ft (1,150 m), on Brooker Mountain immediately north of the deposit. Access to the area is by foot along an old tractor trail from Kantishna.

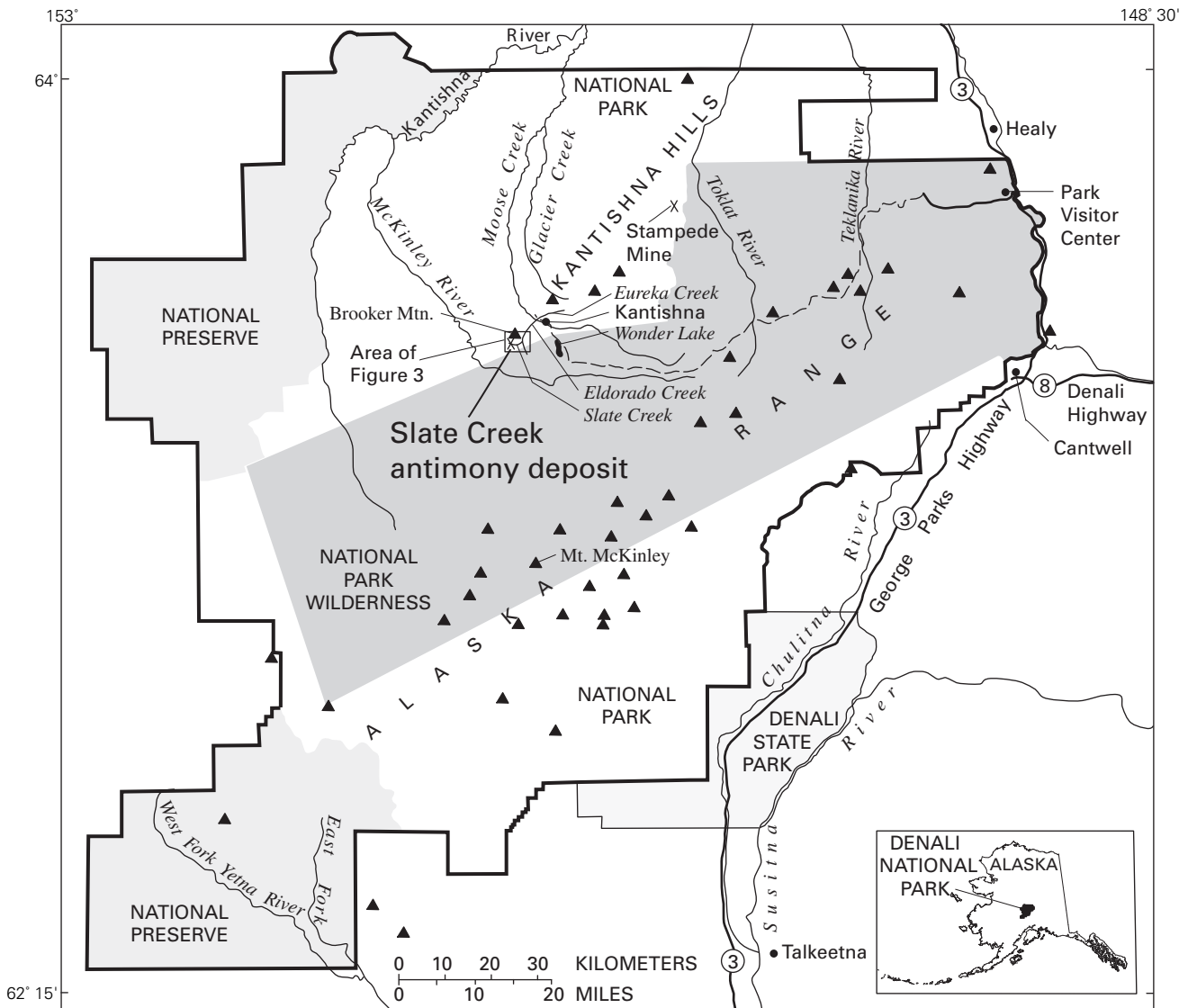


Figure 1. Denali National Park and Preserve, south-central Alaska, showing location of the Slate Creek antimony deposit

In 1997, the NPS recontoured slopes at the Slate Creek antimony deposit, filling in pits and open cuts with mine waste. Just before this study in 1998, the NPS installed rubber dams within the recontoured fill to confine and redirect ground-water flow to a plastic drainpipe (fig. 2B). Ground water from the drainpipe was intended to flow into a buried anoxic carbonate-filtration mechanism to neutralize the acidic water. At the time of this study, the carbonate-filtration mechanism was under construction, and the drainpipe was not yet connected to it (Ken Karle, oral commun., 1998). Thus, the water samples collected at the minesite for this study were pretreatment samples.

Geologic Setting

The earliest geologic and mineral-deposit descriptions of the Kantishna region date from during and immediately after the early 1900s' Gold Rush to interior Alaska (Prindle, 1907; Brooks and others, 1909, p. 56; 1910, p. 44; 1912, p. 38; 1913, p. 45; 1914, p. 68; Brooks, 1916). More extensive studies of the region were conducted by Capps (1918), Davis (1922), Moffit (1933), and Ebbley and Wright (1948). The most extensive recent studies of the geology and mineral deposits of the Kantishna Hills area were by Bundtzen (1978, 1981, 1983, 1994) and Bundtzen and Turner (1978). Mineral-resource reports by the U.S. Bureau of Mines include those by Hawley (1978), Jeske (1984), Fechner and Hoekzema (1986), and White and others (1986).

Basement rocks in the Kantishna Hills area are regionally metamorphosed, range in age from Precambrian to late Paleozoic, and consist of four principal rock units. The oldest and most aerially extensive rocks are Precambrian metamorphic rocks, composed of quartzite, quartz-mica schist, feldspar-biotite schist, gneiss, marble, and greenstone (called the Birch Creek Schist by Bundtzen, 1981). The unit consists of a shallow-water continental-shelf sequence that was metamorphosed to amphibolite facies and later retrograded to greenschist facies (Bundtzen, 1981). The remaining three principal rock units, the Spruce Creek sequence, the Keevy Peak Formation, and the Totatlanika Schist, are regionally metamorphosed to a lower grade than, and tectonically juxtaposed against, the Precambrian metamorphic rocks (Bundtzen, 1981).

Metamorphosed volcanic and sedimentary rocks of the early Paleozoic(?) Spruce Creek sequence (Bundtzen, 1981) consist of chlorite and graphitic schist, marble, and metavolcanic rocks. This sequence, which may represent an early Paleozoic rift environment formed on the Birch Creek shelf deposits (Bundtzen, 1983), is correlated with the Cleary sequence in the Fairbanks district (Bundtzen, 1994). Metasedimentary and metavolcanic rocks of the Keevy Peak Formation (early Paleozoic) and Totatlanika Schist (Late Devonian and Mississippian) are the youngest crystalline rocks in the Kantishna Hills area (Bundtzen, 1981). These deep-water marine and submarine-fan units apparently interfinger locally (Bundtzen, 1983).



Figure 2. Setting of the Slate Creek antimony deposit (fig. 1) in August 1998. *A*, Overview of minesite, showing mine drainage at lower right. Slate Creek flows along right side of disturbed area. Tents in center indicate scale. *B*, Site 98SC010 (pH value, 2.7; conductivity, 1,700 $\mu\text{S}/\text{cm}$; total-dissolved-solids content, 993 mg/L), showing details of minesite, mineralized outcrop, recontoured mine waste, and plastic pipe draining impounded groundwater.

The Kantishna region has been uplifted with the Alaska Range since the middle Tertiary. Undeformed Tertiary mafic to felsic dike swarms and plugs intrude the metamorphic rocks along the crest of the Kantishna Anticline, a major fold structure in the region. Isoclinal to open folds and faults are common. Miocene sandstone and shale, and Quaternary gravel overlie older rock types (Bundtzen, 1981).

As mapped by Bundtzen (1981), the Slate Creek antimony deposit is hosted by undifferentiated medium- to coarse-grained Precambrian garnetiferous quartz-mica schist, massive to laminated quartzite, and feldspar-biotite schist and gneiss. A large plug of Tertiary light-gray porphyritic felsite is mapped about 2.5 mi (4 km) northeast of the mine along Eldorado Creek. No carbonate-bearing units are mapped in the vicinity of the Slate Creek antimony deposit, nor were carbonate minerals observed in the present study.

Mineral Deposits

Mineral deposits in the Kantishna region consist of polymetallic vein deposits, tactite and stratiform occurrences, and placer gold deposits. The vein deposits follow faults and fractures along a semicontinuous, northeast-trending zone extending from Slate Creek to Stampede, about 27 mi (45 km) to the northeast (fig. 1) (Bundtzen, 1981). The vein faults strike N. 30°–70° E. and dip steeply generally southeast but locally northwest. Larger lode deposits occur where the northwestern and southeastern veins intersect. The veins are classified into three types: (1) quartz-arsenopyrite-pyrite-scheelite-gold, (2) galena-sphalerite-tetrahedrite-pyrite-chalcocopyrite with siderite gangue, and (3) stibnite-quartz veins free of other sulfides. Locally, a continuum exists from one type to another (Bundtzen, 1981). Following Lingren (1932), the veins are categorized by depth of formation by Bundtzen (1981) as follows: type 1 veins are hypothermal to mesothermal, type 2 veins are mesothermal to epithermal, and type 3 veins are epithermal. The Spruce Creek sequence, which hosts most of the polymetallic vein deposits, is believed to be a principal metal source for vein deposits in the Kantishna mining district (Bundtzen, 1981). However, the type 3 stibnite-quartz veins are more commonly hosted by Precambrian metamorphic rocks (Bundtzen, 1981).

The Slate Creek antimony deposit is a type 3 epithermal stibnite-quartz(-pyrite) vein deposit, generally lacking other sulfides, that is hosted by Precambrian metamorphic rocks (Bundtzen, 1981). As described by Capps (1918), the deposit is a fissure vein that trends N. 50° E. and dips 82° SE. The vein ranges in thickness from about 2 to 15 ft (0.5–4.6 m) and is composed of a “broken and confused” stockwork of quartz and stibnite in decomposed clay-rich schist (Capps, 1918, p. 325). Red secondary oxidation products include the antimony ochers stibiconite [$\text{Sb}^{3+}\text{Sb}_2^5+\text{O}_6(\text{OH})$] and kermesite ($\text{Sb}_2\text{S}_2\text{O}$) (Capps, 1918). Bundtzen (1981) noted massive stibnite (Sb_2S_3) and quartz, with minor pyrite, boulangerite ($\text{Pb}_5\text{Sb}_4\text{S}_{11}$), ceriantite ($\text{Sb}^{3+}\text{Sb}^{5+}\text{O}_4$), and arsenopyrite (FeAsS). In this study,

stibnite, pyrite, and their alteration products were observed on mine wastepiles, and stibnite-pyrite-quartz cobbles were observed in alluvium downstream. The Slate Creek antimony deposit appears to share most descriptive characteristics with the “simple antimony deposit” model of Bliss and Orris (1986) and, to a lesser degree, with the “stibnite-quartz deposit” model of Seal and others (1995).

Mining History

Bundtzen (1978) reported that Judge James Wickersham first discovered placer gold in the northern Kantishna Hills in 1903 while on his way to an unsuccessful climb of Mount McKinley. Other placer gold discoveries followed shortly—in 1904 by Joe Dalton in the central Kantishna Hills, and in 1905 by Joe Dalton and Joe Quigley on Eureka and Glacier Creeks. A brief, but short-lived, placer gold rush ensued. Sulfide cobbles in sluicelike riffles prompted the search for and discovery of lode deposits.

By 1919, numerous mineralized vein faults containing antimony and base and precious metals were located in a 27-mi (45 km)-long belt trending northeast from Slate Creek to Stampede (Bundtzen, 1981, 1994). Discoveries on upper Slate Creek resulted in the Antimony Nos. 1 through 4 lode and the Antimony Nos. 1 and 2 placer claims (Dames & Moore, 1992). Antimony was sporadically recovered from the Slate Creek antimony deposit, as well as other deposits in the belt, generally during World Wars I and II, the Korean War, and the Vietnam War, because of high antimony prices during these times (Bundtzen, 1983; Dames & Moore, 1992). In 1915–16, a 97-ft (29.6 m)-long tunnel and associated crosscuts were driven near the level of Slate Creek into a wide mineralized shear zone. Drifts were also driven during the early 1940s (Capps, 1918; Ebbley and Wright, 1948). Sporadic surface mining (pits and open cuts) and placering continued on upper Slate Creek from the 1940s until 1983, when mining activities ceased (Bundtzen, 1983; Dames & Moore, 1992). Although records are unclear, the Slate Creek antimony deposit produced about 800,000 lb (362,400 kg) of antimony, principally by hand-sorting stibnite (Jeske, 1984). Unknown amounts of gold and, probably, antimony were produced by placer operations along Slate Creek downstream from the lode deposits (Dames & Moore, 1992). About 40 percent of the antimony produced in Alaska through 1983 came from the Kantishna mineral belt, principally from the Slate Creek and Stampede deposits (Bundtzen, 1983).

Methods

Water, stream-sediment, rock, and soil samples were collected (1) within the disturbed mining area, (2) within the undisturbed mineralized zone surrounding the mining area, and (3) from areas beyond the mineralized zone. Surface water

was collected at 13 sites from small streams, springs, and from a standing prospect pit pool (fig. 3).

Bedload-stream-sediment samples were collected at seven of the stream-water sample sites—six along Slate Creek and its tributaries and one from Eldorado Creek just above its confluence with Slate Creek. Naturally occurring and mine-related mineralized rocks were collected from eight sites, representing mine waste, outcrop, and colluvium. Two soil samples were collected from vegetated tundra that appeared to be undisturbed by historical mining activity, above the naturally mineralized spring at site 98SC011 (fig. 3) and above the prospect pit at site 98SC012. Elements determined, methods used, and details on sample collection and preparation are listed in table 1; site-specific information for the samples collected is listed in table 2.

Stream-water samples collected at each site include (1) an unacidified, filtered water sample for anion analysis; (2) an acidified, filtered sample for trace- and major-cation analysis of dissolved species; and (3) a preserved, filtered sample for mercury content. Before analysis, the unacidified samples were kept on ice in a cooler while in the field, and in a laboratory refrigerator upon return. Samples were filtered (0.45 μm) and acidified to a pH value of <2 to prevent precipitation of metals and bacterial growth (table 1). Other water data col-

lected and recorded on site include temperature, an estimate of the waterflow rate, pH value, conductivity (a measure of electrical conductance: the more ions a solution contains, the higher its conductivity), qualitative turbidity, dissolved-oxygen content, total acidity (a measure of water's base-consuming capacity; done on samples with pH values <5), and total alkalinity (a measure of water's acid-consuming capacity; done on samples with pH values >4.5). These data are listed in table 3, along with sample site descriptive information. Instruments used include Orion pH (model 250A) and conductivity (model 115) meters, calibrated at each site. Also used on site were CHEMetrics kits for alkalinity (titration) and dissolved oxygen (visual comparison), and a Hach acidity kit (titration). The waterflow rate was either determined by a qualitative visual estimate or calculated by timing the fill of a 1-L-volume bottle (table 3).

Many chemical elements were determined by using various analytical techniques (table 1). For descriptions and quality-assurance/quality-control (QA/QC) protocols for most of the analytical methods used, see Arbogast (1996). During the study, QA/QC concerns were addressed by using internal reference standards, field blanks, sample-site duplicates, and analytical duplicates. Reference standards were interspersed with batches of samples, and the analyses of the standards

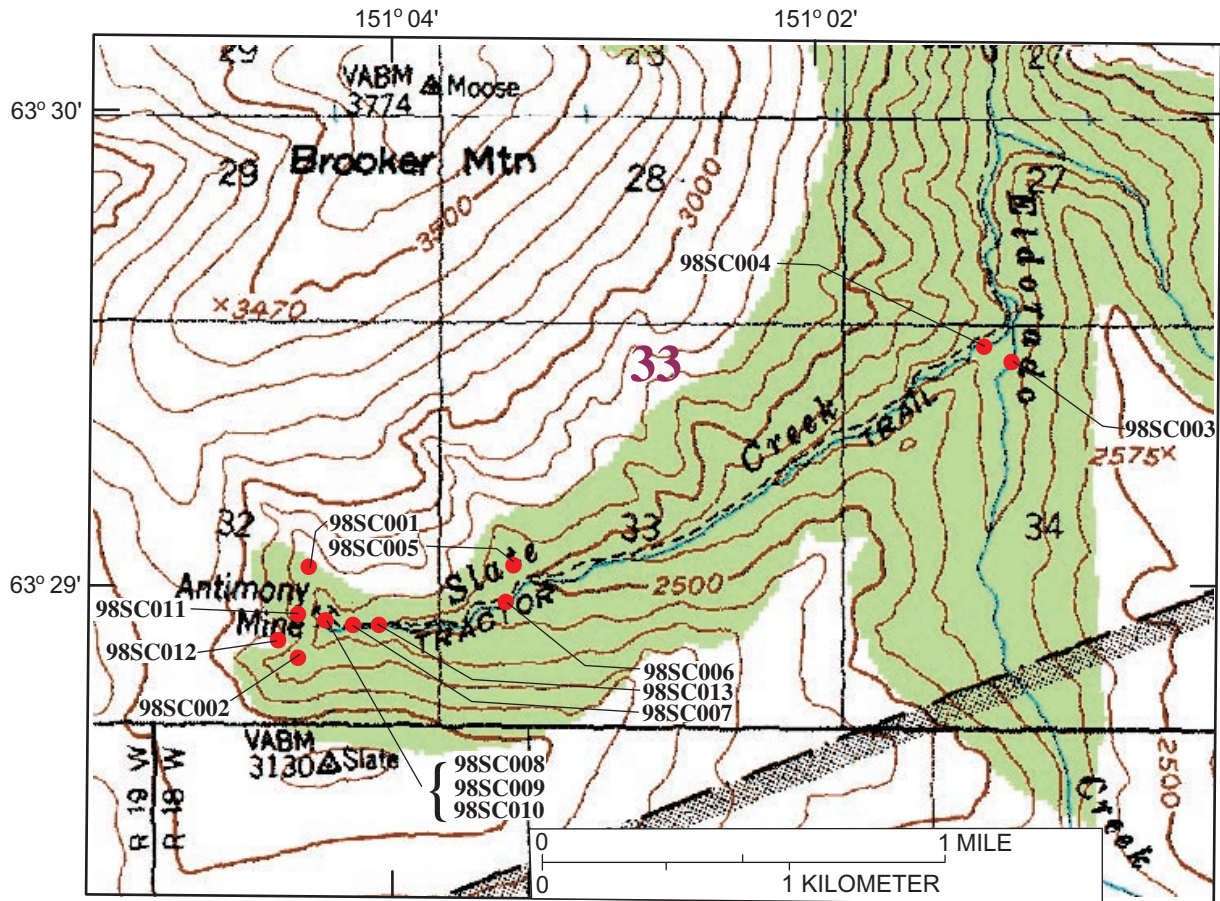


Figure 3. Slate Creek antimony deposit (fig. 1), showing locations of sites where samples were collected. Topography from U.S. Geological Survey Mount McKinley B-3, B-4, C-3, and C-4 1:63,360-scale topographic maps.

Table 1. Elements determined, analytical methods, and collection/preparation procedures used.

[Water samples were filtered at 0.45 μm with disposable filters, collected in acid-rinsed polypropylene bottles, and acidified with ultrapure HNO_3 . Water samples for Hg analysis were filtered as above, collected in acid-rinsed glass bottles with Teflon lids, and preserved with $\text{K}_2\text{Cr}_2\text{O}_7/\text{HNO}_3$. Stream sediments were composited 1-kg samples from active alluvium. In the laboratory, samples were air dried, sieved to minus-80 mesh ($<0.177\text{ mm}$), and pulverized for chemical analysis. Clean quartz sand was pulverized between samples to reduce risk of contamination. Composited rock-chip samples were coarsely crushed to pea-size pieces, split with a Jones splitter, and pulverized as described for sediments. Soil samples were collected from single pits dug in undisturbed B-horizon tundra. Laboratory preparation of the soils followed the same procedures as those used for the sediment samples. Methods: AF, atomic fluorescence; CV, cold-vapor atomic absorption; EP, solid by partial-extraction 10-element inductively coupled plasma atomic-emission spectrometry; ET, solid by total-extraction 40-element inductively coupled plasma atomic-emission spectrometry; EW, water by inductively coupled plasma atomic-emission spectrometry; FA, fire-assay atomic absorption; HY, hydride-generation atomic absorption; IC, ion chromatography; MW, water by inductively coupled plasma mass spectrometry; TS, Leco automated total sulfur analyzer. See Arbogast (1996) for operational details]

Sample media	Method	Elements determined
Water, filtered/acidified	MW	Ag, Al, As, Au, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cs, Cu, Dy, Er, Eu, Fe, Ga, Gd, Ge, Ho, In, K, La, Li, Mg, Mn, Mo, Na, Nd, Ni, P, Pb, Pr, Rb, Re, Sb, Se, Sm, Sr, Tb, Th, Ti, Tl, Tm, U, V, W, Y, Yb, Zn
	EW	Ag, Al, As, B, Ba, Be, Ca, Cd, Co, Cr, Cu, Fe, K, Li, Mg, Mn, Mo, Na, Ni, P, Pb, Sb, Si, Sr, Ti, V, Zn
	AF	Hg
Water, filtered/not acidified	IC	Cl^- , F^- , NO_3^- , SO_4^{2-}
Sediment, rocks, and soils	ET	Ag, Al, As, Au, Ba, Be, Bi, Ca, Cd, Ce, Co, Cr, Cu, Eu, Fe, Ga, Ho, K, La, Li, Mg, Mn, Mo, Na, Nb, Nd, Ni, P, Pb, Sc, Sn, Sr, Ta, Th, Ti, U, V, Y, Yb, Zn
	EP	Ag, As, Au, Bi, Cd, Cu, Mo, Pb, Sb, Zn
	HY	As, Sb, Se, Te, Tl
	FA	Au
	CV	Hg
	TS	total S

were checked to assure that reported values were within ± 20 percent of the accepted values. Sample-site duplicates were collected for waters and sediment at one site (sites 98SC007, 98SC007D, fig. 3), and qualitative inspection of the data tables indicates good agreement in analyses between the duplicates. This result suggests minimal combined sample-site and analytical variance.

In discussing water chemistry, we emphasize the following significant inorganic parameters listed in the Alaska Department of Environmental Conservation (ADEC)'s drinking-water standards (Alaska Department of Environmental Conservation, 2000) and by the U.S. Environmental Protection Agency (EPA) (Environmental Protection Agency, 1999a): pH value and Ag, Al, As, Ba, Be, Cd, Cl^- , Cr, Cu, F^- , Fe, Hg, Mn, Na, Ni, NO_3^- , Pb, Se, SO_4^{2-} , Tl, and Zn contents. Primary maximum contaminant levels (MCLs) are regulatory water-quality action levels established by the ADEC, whereas secondary MCLs are nonregulated, recommended water-quality goals. We also emphasize the following toxic pollutants listed by the EPA (Environmental Protection Agency, 1993) with respect to freshwater aquatic-life standards: Ag, Cd, Cr(III), Cu, Pb, Ni, and Zn contents.

The water classifications used herein, based on relative amounts of major cations and anions, follow those of Piper (1944), Hem (1985), and Drever (1997, app. 1, fig. 2). For water samples where carbonate (CO_3^{2-}) and bicarbonate (HCO_3^-) are present, bicarbonate is overwhelmingly dominant; thus, the term "bicarbonate" is used exclusively when discussing these species. Carbonate and bicarbonate concentrations were determined from measured pH and total alkalinity, using the equations of Deutsch (1997, p. 13–14), which assume that carbonate alkalinity is about equal to total alkalinity, a reasonable assumption for most natural waters (Hem, 1985, p. 106; Drever, 1997, p. 46).

The subjective term "anomalous" is used in a relative sense with respect to the average crustal abundances listed by Smith and Huyck (1999, table 2.8), to the background data on various rock types and sample media provided by Rose and others (1979) and Levinson (1980), and to the examination of data distributions for the samples collected in this study. The term "highly anomalous" indicates concentrations two or more orders of magnitude above the threshold values, whereas "lower-level anomalous" concentrations are higher than, but within an order of magnitude of, the threshold values.

Table 2. Site-descriptive information for samples collected from the Slate Creek antimony deposit.

[Latitude and longitude determined with high-precision Global Positioning System (GPS) unit; datum and spheroid used were NAD27AK and Clarke 1866, respectively. XY error, GPS latitude/longitude location error. FeOx, iron oxides; MnOx, manganese oxides; NPS, National Park Service. Do., ditto]

Site (fig. 3)	Latitude °N.	Longitude °W.	XY error (± ft)	Elevation (ft)	Date collected	Location information
Naturally mineralized						
98SC001	63.48269	151.07249	45	2720	8/11/1998	NW fork, head of Slate Creek; below junction of two small streams.
98SC002	63.48036	151.07497	26	2760	8/11/1998	SW fork, head of Slate Creek; below junction of two small streams.
98SC011	63.48187	151.07275	27	2770	8/14/1998	About 150 ft W. of Slate Creek antimony deposit; topographic depression above ferricrete bank along Slate Creek; located along old roadcut to nearby prospect pit to south.
98SC013	63.48166	151.06240	26	2610	8/14/1998	Spring along S side of Slate Creek about 1,800 ft below waste piles; appears to be unaffected by mining.
Mine						
98SC008	63.48216	151.07153	30	2710	8/13/1998	Hand-dug trench; upper end of rubber barrier in mine waste; trench/dam recently installed by NPS for remediation work; site is within recently recontoured mine waste.
98SC009	63.48172	151.07089	22	2670	8/13/1998	Mine drainage at Slate Creek antimony deposit; on mine waste; site is within recently recontoured mine waste.
98SC010	63.48178	151.07172	21	2690	8/13/1998	Inlet to carbonate-filtration mechanism recently installed by NPS on mine wastepile; site is within recently recontoured mine waste.
98SC012	63.48149	151.07357	34	2810	8/14/1998	Hillside about 300 ft southwest of Slate Creek antimony deposit reclamation site.
Downstream from and influenced by mine						
98SC004	63.49183	151.02053	28	2160	8/12/1998	Mouth of Slate Creek upstream of junction with Eldorado Creek.
98SC006	63.48331	151.05628	32	2520	8/12/1998	Slate Creek, about 100 ft upstream from side drainage at site 98SC005 (fig. 3), about 0.5 mi downstream from Slate Creek antimony deposit.
98SC007	63.48165	151.06550	32	2630	8/13/1998	Slate Creek just downstream from mine wastepiles, about 100 ft below small stream flowing behind camp.
98SC007D	63.48165	151.06550	32	2630	8/13/1998	Duplicate of site 98SC007.
Distal from mine and mineralized area						
98SC003	63.49155	151.01726	27	2150	8/12/1998	Eldorado Creek, about 500 ft above confluence with Slate Creek.
98SC005	63.48345	151.05612	29	2530	8/12/1998	Unnamed tributary to Slate Creek entering from the north about 0.5 mi downstream from Slate Creek deposit.

Table 2. Site-descriptive information for samples collected from the Slate Creek antimony deposit—Continued.

Site (fig. 3)	Site description	Bedrock geologic information
98SC001	Flowing stream; undisturbed site upstream of mine workings in heavy alder and willow cover; moderate gradient, swift; site is probably representative of premining conditions at the Slate Creek antimony deposit; no visible contamination.	None at site.
98SC002	Flowing stream; undisturbed site upstream of mine workings; approximately on NE, strike of the mineralized vein system; site is probably representative of premining conditions at the Slate Creek antimony deposit; no visible contamination.	Shattered, siliceous muscovite-quartzite; cut by thin quartz veins; FeOx and lesser MnOx on cleavage surfaces; possibly disseminated pyrite.
98SC011	Naturally mineralized spring; abundant FeOx precipitating on leaves, twigs, and other organic debris; site is probably representative of premining conditions at the Slate Creek antimony deposit; no visible contamination.	Ferricrete cementing muscovite schist in switchback 30 ft above site; site is on strike with the NE.-trending vein system at the Slate Creek deposit.
98SC013	Naturally mineralized spring; site is probably representative of premining conditions at the Slate Creek antimony deposit; no visible contamination.	None at site.
98SC008	Flowing seep at minesite; trench with ponded spring water.	Pyritic quartz-mica schist (with stibnite); horizons of graphite schist; well-cleaved/friable; sparse green mineral (epidote?); ore-bearing quartz vein has been mined out, leaving mineralized wallrock.
98SC009	Flowing mine drainage; within the last month, fine carbonate was scattered over the mine wastepiles and is evident locally in sediment in the mine drainage.	Well-foliated quartz-muscovite schist with graphite schist horizons; local yellow-green staining and FeOx suggest weathering sulfides.
98SC010	Mine drainage; ground water flowing from black plastic pipe coming up from below ground; this pipe will be attached to the buried carbonate filter downgradient from this spot.	Pyritic quartz-mica schist (with stibnite); horizons of graphite schist; well-cleaved/friable; sparse green mineral (epidote?); ore-bearing quartz vein has been mined out, leaving mineralized wallrock.
98SC012	Standing pool of spring/rain water in prospect pit; no visible contamination.	Highwall along pit is ferricrete-cemented muscovite schist; pit is on strike with NE.-trending vein at mine; abundant disaggregated stibnite in wastepile.
98SC004	Flowing stream; swift, about 12 ft wide, 6–10 in. deep; downstream of mine and mineralized area.	Interbedded muscovite schist/quartz-muscovite schist; contains minor graphitic schist horizons; two cleavage sets orthogonal to foliation; FeOx-stained joints.
98SC006	Flowing stream; orange-stained alluvium common from here upstream; about 10–15 ft wide, 4–6 in. deep, swift; downstream of mine and mineralized area.	None at site.
98SC007	Flowing stream below mine; orange-stained, no vegetation or algae in active channel; about 12 ft wide, 4–6 in. deep; steel cable, milled wood in channel.	Do.
98SC007D	Duplicate of site 98SC007.	Do.
98SC003	Flowing stream; upstream of confluence with Slate Creek; about 6 ft wide, about 10 in. deep; no visible contamination; distal from minesite.	Do.
98SC005	Flowing stream; drainage about 3 ft across, 1 ft deep, swift, moderate to high gradient; no visible contamination; distal from minesite.	Do.

Table 3. Onsite data for water samples collected from the Slate Creek antimony deposit and vicinity.

[cfs, cubic feet per second; diss., dissolved. Alkalinity and acidity are expressed as equivalent CaCO₃. Flow rate: -v, qualitative visual estimate, -c, calculated. Do., ditto]

Site (fig. 3)	Temp (°C)	Flow rate	Flow unit	pH	Conductivity (μS/cm)	Diss. O ₂ (mg/L)	Alkalinity (mg/L)	Acidity (mg/L)	Water color	Water odor	Qualitative turbidity
Naturally mineralized											
98SC001	6	3-v	cfs	6.9	200	9	60	--	clear	none	none
98SC002	5.3	1-v	cfs	7.2	300	9	130	--	clear	none	none
98SC011	4.6	23-v	L/min	5.6	750	3	180	--	clear	strong sulfur	none
98SC013	7.1	11-c	L/min	7.7	300	9	57	--	clear	strong sulfur	none
Mine											
98SC008	10.3	0-v	standing	2.9	1,320	6	0	520	clear	none	none
98SC009	11	40-c	L/min	4.9	770	5	<10	280	clear	none	slightly tan
98SC010	9.6	6-c	L/min	2.7	1,700	5	0	620	clear	none	slight
98SC012	6.7	0-v	standing	5.8	990	5	110	--	clear	none	none
Downstream of and influenced by mine											
98SC004	6.2	12-v	cfs	7.5	260	9	63	--	clear	none	slight
98SC006	7	6-v	cfs	7.5	280	9	70	--	clear	none	slight
98SC007	7.6	4-v	cfs	6.9	260	9	78	--	clear	none	none
98SC007D	7.6	4-v	cfs	6.9	260	9	76	--	clear	none	none
Distal from mine and mineralized area											
98SC003	3.6	6-v	cfs	7.3	200	10	85	--	clear	none	none
98SC005	6.1	2-v	cfs	7.8	130	9	60	--	clear	none	none

Results

Water Samples

Analytical results for water samples are listed in table 4. The charge balance (a ratio of cations to anions for major cations and anions) ranged from 1.0 to 1.2 (mean, 1.08; $n=11$) for most samples; however, three water samples collected from the Slate Creek antimony deposit proper (sites 98SC008, 98SC009, 98SC010, fig. 3) had charge balances of 0.7, 0.8, and 0.7, respectively. This divergence from unity probably results from their highly acidic, metalliferous composition, which can cause analytical interferences, or, possibly, from the abundance of ionic species that were not included in the charge balance.

The waters draining the Slate Creek antimony deposit were found to have the lowest pH values (2.7–5.8) (table 3). The lowest pH values were measured in samples of mine-related waters directly derived from the recontoured mine waste (sites 98SC008, 98SC009, 98SC010, fig. 3); these three water samples also had total acidities ranging from 280 to 620 mg/L (as equivalent CaCO₃). All other stream-water samples had near-neutral pH values. Samples from the naturally mineralized springs had pH values of 5.6 and 7.7 (sites 98SC011 and 98SC013, respectively). Conductivities ranged from 130 to 200 μS/cm in water samples from the two

distal streams (sites 98SC003, 98SC005), from 200 to 300 μS/cm in water samples from the two naturally mineralized streams (sites 98SC001, 98SC002), from 770 to 1,700 μS/cm in water samples from the four minesites, and from 260 to 280 μS/cm in water samples from the three sites along Slate Creek downstream from the mineralized area (sites 98SC004, 98SC006, 98SC007, 98SC007D). Samples from the naturally mineralized springs had conductivities of 750 and 300 μS/cm (sites 98SC011 and 98SC013, respectively). Dames & Moore (1992) noted the naturally mineralized spring sampled at site 98SC011 and stated that this “groundwater seep” had a pH value of 6.4, a conductivity of 650 μS/cm, and a “severe orange-brown discoloration,” as also observed in this study.

Alkalinities (as equivalent CaCO₃) at the minesite ranged from 0 mg/L (pH value, <3; sites 98SC008, 98SC010, fig. 3; table 3) to 110 mg/L, in a sample of standing water from a prospect pit (pH value, 5.8; site 98SC012). Alkalinities in samples from the naturally mineralized springs were 180 mg/L (site 98SC011, the highest value measured in this study) and 57 mg/L (site 98SC013). Alkalinities in water samples from the two distal streams were 60 and 85 mg/L, and those in water samples from the two naturally mineralized streams were 60 and 130 mg/L. Alkalinities in water samples from Slate Creek below the mine and mineralized area ranged from 63 to 78 mg/L (mean, 72 mg/L; $n=4$), only slightly lower than those in water samples from the distal streams.

Waters ranged in major-anion composition from bicarbonate to sulfate dominant and were calcium-magnesium waters with respect to major cations (fig. 4). The four mine-related water samples (sites 98SC008, 98SC009, 98SC010, 98SC012, fig. 3) were all sulfate dominant. This contrasts with the bicarbonate dominance in water samples from the two distal streams and the two naturally mineralized streams (sites 98SC003, 98SC005, 98SC001, and 98SC002, respectively). Water samples collected along Slate Creek downstream from the mine and mineralized area were intermediate in composition with respect to carbonate and sulfate. The sample from the naturally mineralized spring at site 98SC013 was sulfate dominant, whereas the sample from the naturally mineralized spring at site 98SC011 was intermediate in composition with respect to carbonate and sulfate. Both of these springs had strong sulfurous odors and the latter was precipitating abundant iron oxide.

TDS contents were highest in the four mine-related water samples (table 4), ranging from 671 to 993 mg/L, followed by those in the water sample from the naturally mineralized spring within the mineralized zone (544 mg/L; site 98SC011, fig. 3), and in the water sample from a naturally mineralized stream (316 mg/L; site 98SC002). This stream-water sample was collected upstream from the minesite, approximately on strike with the northeastward trend of the mineralized vein system. TDS contents dropped quickly in stream waters along Slate Creek immediately below the minesite and continued to drop at sites downstream (table 4).

The naturally mineralized springs (sites 98SC011, 98SC013, fig. 3) exceeded ADEC primary and secondary drinking-water MCLs for SO_4^{2-} , As, Fe, Mn, Sb, and TDS contents (Alaska Department of Environmental Conservation, 2000). The pH value in the sample from one of the naturally mineralized springs (site 98SC011) was outside the acceptable MCL range of 6.5 to 8.5. The Mn and Sb contents in water samples from the naturally mineralized streams collected above the minesite (sites 98SC001, 98SC002) were close to, but nevertheless exceeded, MCLs, and Fe content was high but below the MCL. The distal streams did not exceed MCLs.

With respect to the surface-water averages of Martin and Whitfield (1983), Meybeck (1988), and Hem (1985), the following elements were found to be abundant in waters from the four mine-related sites: SO_4^{2-} , Al, As, Co, Fe, Mn, Ni, Sb, Zn, TDS, and, to a lesser degree, Ba, Cd, Cu, Th, U, and rare-earth-elements. As indicated in table 4, several of these cations and anions (SO_4^{2-} , As, Fe, Mn, Ni, Sb) exceeded ADEC primary and secondary MCLs for drinking water. The pH values at these four sites were also outside the acceptable MCL range. However, at site 98SC007 (fig. 3) below the mine wastepiles, all of the above-listed elements quickly dropped in concentration shortly upon mixing with Slate Creek. Persisting downstream along Slate Creek from site 98SC007 at concentrations exceeding established MCLs were As (23 $\mu\text{g/L}$, site 98SC007), Fe (0.87–2.3 mg/L, still exceeding the MCL at site 98SC006), Mn (61–330 $\mu\text{g/L}$, still exceeding the MCL at site

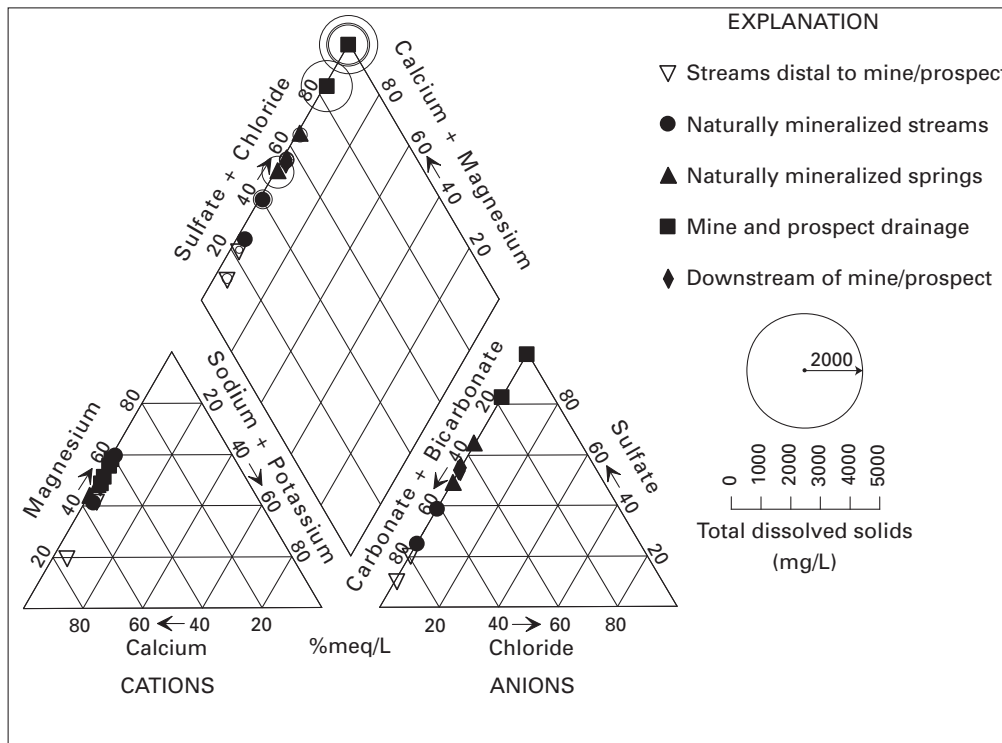


Figure 4. Piper diagram showing major-ion compositions in surface waters. Squares, samples from mine and prospect; inverted triangles, samples from streams distal from mine and prospect; dots, samples from naturally mineralized streams; triangles, samples from naturally mineralized springs; diamonds, samples from mixed stream downstream from mine and mineralized area. After Piper (1944).

Table 4. Analytical data for water samples collected from the Slate Creek antimony deposit and vicinity.

[The following elements were not detected at the lower detection limits (in micrograms per liter): Au (0.01), B (10), Bi (0.01), Hf (0.05), Hg (0.005), Nb (0.02), Re (0.02), Ta (0.02), Te (2), W (0.02), and Zr (0.05). mg/L, milligrams per liter; µg/L, micrograms per liter; EW, inductively coupled plasma atomic-emission spectrometry; IC, ion chromatography; MW, inductively coupled plasma mass spectrometry. HDN, calculated hardness; TDS, calculated total dissolved solids. H₂O sources: DN, downstream from minesite; DS, distal from mineralized area; MINE, minesite; NM, naturally mineralized; SP, spring; ST, stream. MCL, primary maximum contaminant level (bold); 2MCL, secondary maximum contaminant level (italic). See text for explanation of MCL values]

Site (fig. 3)	Water source	Channel-bed description
98SC001	Stream	Heavy orange FeOx precipitate on alluvium; alluvium is dominantly muscovite schist and quartzite, with lesser vein quartz; pyrite and stibnite in vein quartz.
98SC002	Stream	Organic-rich, very heavily coated with FeOx; in willow thicket; sparse FeOx-coated pebbles.
98SC011	Seep spring	Extensive orange FeOx coating organic debris and minor mica schist colluvium.
98SC013	Spring	Leaves and other organic debris on mica schist; no FeOx staining.
98SC008	Mine drainage	Fine mud settled on mine waste used as fill.
98SC009	Mine drainage	Heavy FeOx slime covering mine waste; sparse stressed willow and alder along drainage in less disturbed areas.
98SC010	Mine drainage	Black plastic pipe.
98SC012	Pool in prospect pit	FeOx mud and slime on leaves, organic debris, and angular rock fragments.
98SC004	Stream	Rocky, sparsely vegetated; willow-spruce-grass banks.
98SC006	Stream	Open, rocky, no algae growth and rocks are not slippery along entire length of Slate Creek; pervasive FeOx staining.
98SC007	Stream	Rocky, angular cobbles, heavily coated with FeOx, abundant FeOx fines.
98SC007D	Stream	Do.
98SC003	Stream	Rocky, algae-covered; no obvious staining; creek in grass-moss-willow meadow.
98SC005	Stream	Heavily overgrown with willow, algae in stream.

Site (fig. 3)	H ₂ O source	F ⁻ _mg/L_IC	Cl ⁻ _mg/L_IC	SO ₄ ²⁻ _mg/L_IC	NO ₃ ⁻ _mg/L_IC	Ag_µg/L_MW	Al_µg/L_MW	As_µg/L_MW	Ba_µg/L_MW
MCL	<i>2MCL</i>	4	<i>2</i>	250	<i>250</i>	44	--	10	200
98SC001	NM, ST	.1	.1	20	<.4	.01	6.7	4.4	5
98SC002	NM, ST	.2	.3	81	<.4	<.01	2.2	6.7	8.2
98SC011	NM, SP	.2	.6	180	<.4	.20	230	32	27
98SC013	NM, SP	.2	.1	100	<.4	<.01	7.7	27	4
98SC008	MINE	1.1	1.6	570	<.4	.02	2,000	460	3
98SC009	MINE	.8	.6	520	<.4	.06	1,100	36	32
98SC010	MINE	1.5	2.0	800	<.4	.02	3,700	970	3
98SC012	MINE	<.1	.5	520	<.4	.03	3.7	2	5
98SC004	DN, ST	.1	.2	70	.8	<.01	14	4.5	7.8
98SC006	DN, ST	.4	.2	84	<.4	<.01	31	9.7	7.7
98SC007	DN, ST	.1	.2	89	<.4	<.01	54	23	7.6
98SC007D	DN, ST	.1	.2	88	<.4	<.01	50	22	7.7
98SC003	DS, ST	.1	.3	11	.9	<.01	6.5	2	15
98SC005	DS, ST	.1	.1	16	.5	.03	6.5	3.9	5

Site (fig. 3)	Be_µg/L_MW	Ca_mg/L_EW	Cd_µg/L_MW	Ce_µg/L_MW	Co_µg/L_MW	Cr_µg/L_MW	Cu_µg/L_MW	Dy_µg/L_MW	Er_µg/L_MW
MCL	<i>2MCL</i>	4	--	5	--	--	100	1,300	--
98SC001	<.05	18	<.02	.02	.08	<.1	2	.01	<.005
98SC002	<.05	37	<.02	.01	.5	<.1	.8	<.005	<.005
98SC011	.2	86	<.02	1.5	4	<.1	1	.24	.22
98SC013	<.05	35	<.02	<.01	.07	<.1	.7	<.005	<.005
98SC008	1.1	40	3.4	40	160	6	140	4.4	2.3
98SC009	.7	57	1.9	16	140	<.1	54	1.8	.98
98SC010	1	45	4.4	54	220	8	190	6.1	3.3
98SC012	<.05	110	.05	.09	17	<.1	2	.01	.02
98SC004	<.05	29	.06	.05	.8	<.1	2	.008	<.005
98SC006	<.05	31	.05	.2	3.6	<.1	2	.02	.02
98SC007	<.05	33	.1	.4	5.4	<.1	3	.04	.04
98SC007D	<.05	33	.07	.4	5.4	<.1	3	.04	.03
98SC003	<.05	33	<.02	<.01	.3	<.1	<.5	<.005	<.005
98SC005	<.05	15	.2	.03	2.8	<.1	1	.008	.008

Table 4. Analytical data for water samples collected from the Slate Creek antimony deposit and vicinity—Continued.

Site (fig. 3)	Eu_μg/L_MW	Fe_mg/L_EW	K_mg/L_EW	La_μg/L_MW	Li_μg/L_MW	Mg_mg/L_EW	Mn_μg/L_MW	Mo_μg/L_MW	Na_mg/L_EW
MCL/2MCL	--	0.3	--	--	--	--	50	--	250
98SC001	<.005	.064	.24	.03	1.1	8.1	12	.2	.76
98SC002	<.005	.35	.34	<.01	2	34	60	.03	.52
98SC011	.053	19	.62	.92	5	41	1,000	3	.49
98SC013	<.005	<.05	.15	<.01	1.7	20	.95	<.02	.52
98SC008	1	100	.5	18	3.4	26	5,000	.4	.46
98SC009	.35	78	.64	7.9	4	34	5,700	.98	.63
98SC010	1.3	170	.61	24	2.8	35	6,500	.3	.46
98SC012	<.005	2.4	.51	.2	4.2	94	3,000	.56	.39
98SC004	<.005	.13	.29	.04	1.7	17	61	.07	.8
98SC006	.008	.87	.3	.1	1.8	19	240	.05	.68
98SC007	.007	2.3	.29	.2	1.3	21	330	.1	.73
98SC007D	.008	2.2	.28	.2	1.7	21	330	.07	.7
98SC003	<.005	<.05	.52	<.01	2	5.5	1.1	.4	1.8
98SC005	<.005	<.05	.26	.04	1.1	7.4	11	.55	.67

Site (fig. 3)	Nd_μg/L_MW	Ni_μg/L_MW	Gd_μg/L_MW	P_μg/L_EW	Pb_μg/L_MW	Pr_μg/L_MW	Rb_μg/L_MW	Sb_μg/L_MW	Sc_μg/L_MW
MCL/2MCL	--	100	--	--	15	--	--	6	--
98SC001	.03	1.5	.005	<50	<.05	.01	.2	2.3	<.1
98SC002	.01	3	<.005	<50	<.05	<.01	.2	14	<.1
98SC011	.78	14	.24	<50	.2	.2	.6	.7	<.1
98SC013	<.01	1.9	<.005	<50	<.05	<.01	.1	8.9	<.1
98SC008	17	320	4.4	170	2.4	4.5	1.6	120	5
98SC009	6.3	290	1.6	<50	.4	1.7	1.7	35	.9
98SC010	24	450	6.1	320	4.5	6.2	2	220	6.2
98SC012	.02	53	.02	<50	<.05	<.01	.9	.3	<.1
98SC004	.02	4.9	.007	<50	<.05	.01	.2	100	<.1
98SC006	.06	11	.03	<50	<.05	.03	.3	190	<.1
98SC007	.2	14	.03	<50	<.05	.05	.3	120	<.1
98SC007D	.2	14	.056	<50	<.05	.03	.3	120	<.1
98SC003	.01	1.1	<.005	<50	<.05	<.01	.1	.52	.2
98SC005	.05	2.3	.01	<50	<.05	.01	.3	1.3	<.1

Site (fig. 3)	Se_μg/L_MW	Si_mg/L_EW	Sm_μg/L_MW	Sn_μg/L_MW	Sr_μg/L_EW	Tb_μg/L_MW	Th_μg/L_MW	Ti_μg/L_MW	Tl_μg/L_MW
MCL/2MCL	50	--	--	--	--	--	--	--	2
98SC001	<.2	2.6	<.01	<.05	68	<.005	<.005	<.1	.2
98SC002	<.2	1.8	<.01	.07	100	<.005	<.005	1.4	<.05
98SC011	.4	3.2	.1	.1	210	.05	.006	2.3	<.05
98SC013	<.2	2	<.01	<.05	150	<.005	<.005	1.3	<.05
98SC008	2	3.2	3.7	.05	170	.78	34	6.6	.07
98SC009	.8	4.1	1.2	.05	220	.32	.04	5.3	<.05
98SC010	2	3.8	5.3	<.05	210	1.1	44	8.4	.1
98SC012	.5	1.8	<.01	<.05	250	<.005	<.005	7.2	<.05
98SC004	<.2	2.6	<.01	<.05	120	<.005	.006	1	<.05
98SC006	.3	2.4	.01	<.05	120	.006	.02	.8	<.05
98SC007	.3	2.4	.02	.06	110	.009	.04	1.2	.05
98SC007D	<.2	2.4	.04	<.05	110	.009	.03	.8	<.05
98SC003	.4	4.4	<.01	<.05	130	<.005	<.005	<.1	.1
98SC005	<.2	2.6	<.01	<.05	69	<.005	<.005	.2	.7

Site (fig. 3)	Tm_μg/L_MW	U_μg/L_MW	V_μg/L_MW	Y_μg/L_MW	Yb_μg/L_MW	Zn_μg/L_MW	TDS_mg/L	HDN_mg/L
MCL/2MCL	--	--	--	--	--	5,000	500	--
98SC001	<.005	.18	<.1	.04	<.01	1	126	78
98SC002	<.005	2.2	<.1	.03	<.01	2	316	232
98SC011	.04	.04	.5	2.6	.2	20	544	383
98SC013	<.005	.02	<.1	<.01	<.01	2	230	170
98SC008	.33	20	3	21	1.7	1,200	710	207
98SC009	.13	5.7	<.1	11	.75	800	671	282
98SC010	.43	25	5.1	30	2.5	1,600	993	256
98SC012	<.005	.02	<.1	.66	<.01	240	868	661
98SC004	<.005	.85	<.1	.08	<.01	10	201	142
98SC006	<.005	.67	<.1	.2	.02	20	227	156
98SC007	.005	.95	<.1	.4	.02	34	246	169
98SC007D	<.005	.93	<.1	.4	.03	28	243	169
98SC003	<.005	.38	<.1	.02	<.01	<.5	166	105
98SC005	<.005	.15	<.1	.06	<.01	62	119	68

98SC004, at the mouth of Slate Creek), and Sb (100–190 µg/L, still 100 times the MCL at site 98SC004). To summarize, (1) As, Fe, Mn, and Sb contents exceeded MCLs immediately below the mine and mineralized area; (2) by about 0.5 mi (0.8 km) downstream from the mine and mineralized area, Fe, Mn, and Sb contents exceeded MCLs, and the As content was very close to, but still below, the MCL; and (3) at the mouth of Slate Creek, about 1.8 mi (2.9 km) downstream from the mine and mineralized area, only Mn and Sb contents exceeded MCLs, and Fe and As contents were high but below MCLs and below concentrations in a naturally mineralized stream above the mineralized area.

In a limited study with two water samples, one above and one immediately below the mine and mineralized area, Dames & Moore (1992) measured Fe contents exceeding the MCL in the upstream naturally mineralized sample, and Sb and Fe contents exceeding MCLs at the lower site. They did not detect As or Hg (at 0.2 µg/L), and they did not analyze for Mn in their reconnaissance study. In this study, Hg was not detected in any water samples (at 0.005 µg/L).

The dissolved-cation concentrations listed in table 4 were compared against EPA freshwater aquatic-life standards (Environmental Protection Agency, 1993) for the following toxic pollutants: Ag, As, Cd, Cr(III), Cu, Pb, Ni, and Zn (all but As are hardness dependent). Only total Cr, not individual Cr species, was determined in this study. However, in all samples, total Cr contents were a tenth of the EPA threshold values for Cr(III). Only three minesite waters contained metallic-ion concentrations in excess of EPA standards for freshwater aquatic life (table 5), and none of the other water samples collected exceeded EPA freshwater aquatic-life standards. The acute and chronic standards listed in table 5 should be considered only as guidelines; the ADEC may have aquatic-life guidelines that supercede these. Furthermore, the EPA is currently establishing new guidelines for aquatic life (Environmental Protection Agency, 1999b). Acute and chronic standards are hardness dependent and thus vary from sample to sample in table 5.

Solid Samples

Analytical results for stream-sediment, rock, and soil samples are listed in table 6. The following elements were not detected in any samples at the parenthetical lower detection limits (in parts per million): Ag (0.08), Eu (2), Ho (4), Ta (40), and U (100). For comparison with the following discussion, worldwide crustal abundances are 1.7 to 5 ppm for As and 0.15 to 1 ppm for Sb, and average concentrations in U.S. soils are 5.2 ppm for As and 0.5 ppm for Sb (Smith and Huyck, 1999). Threshold values, above which concentrations are considered anomalous in this study, are listed in table 6.

Arsenic and antimony stand out, with highly anomalous contents in stream-sediment and soil samples relative to crustal abundances (Smith and Huyck, 1999) and to background concentrations in the various rock types listed by Rose and others (1979). Minus-80 mesh (<0.177 mm) sediment

Table 5. Analytical data for three water samples from the Slate Creek antimony deposit and vicinity containing metallic-ion concentrations exceeding EPA standards for freshwater aquatic life.

[All values in micrograms per liter. Acute standard, 1-hour exposure; chronic standard, 4-day exposure]

Element	Sample		
	98SC008	98SC009	98SC010
Total As -----	460	--	970
Acute standard -----	360	--	360
Chronic standard -----	190	--	190
Total Cd -----	3.4	--	4.4
Chronic standard -----	2.03	--	2.4
Total Cu -----	140	54	190
Acute standard -----	35.7	46.8	43.6
Chronic standard -----	22.3	28.5	26.8
Total Ni -----	320	--	450
Chronic standard -----	295	--	354
Total Zn -----	1,200	800	1,600
Acute standard -----	219	280	263
Chronic standard -----	199	254	238

samples from the two distal streams (sites 98SC003, 98SC005, fig. 3) contained 60 and 440 ppm As, respectively. Sediment samples from the two naturally mineralized streams (sites 98SC001, 98SC002) had highly anomalous As contents of 830 and 2,300 ppm—the highest As content in stream sediment found in this study. Samples of naturally mineralized tundra soils (sites 98SC011, 98SC012) had lower-level anomalous As contents of 56 and 63 ppm, respectively. Stream-sediment samples downstream from the mine and mineralized area had As contents ranging from 1,100 to 2,100 ppm (mean, 1,700 ppm; $n=4$; sites 98SC004, 98SC006, 98SC007, 98SC007D), decreasing from site 98SC007 just below the wastepiles to the mouth of Slate Creek (fig. 3). Sediment samples from the two distal streams contained 12 and 84 ppm Sb, with the lowest value from Eldorado Creek. Sediment samples from the two naturally mineralized streams contained 130 and 450 ppm Sb, and samples from the naturally mineralized soils contained 43 and 85 ppm Sb. Highly anomalous Sb contents (1,200–6,000 ppm; mean, 3,850 ppm; $n=4$) were measured in the stream-sediment samples from Slate Creek downstream from the mineralized area.

Several other elements were measured in anomalously high concentrations in stream-sediment and soil samples. A highly anomalous Mn content (29,000 ppm) was measured in naturally mineralized sediment at site 98SC002 (fig. 3), and lower-level anomalous Mn contents of 1,500 to 2,600 ppm (mean, 1,740 ppm; $n=5$) were measured in nearly all the other stream-sediment samples, whether from the distal streams or at sites downstream from the mine and mineralized area. Other elements measured in varyingly high concentrations in one or more of the samples include (1) lower-level anomalous contents of Bi, Cd, Fe, Hg, Zn, and, possibly, Se, Te, and Zn in sediment samples from the distal streams; (2) highly anoma-

Table 6. Descriptive and analytical data for sediment, rock, and soil samples collected from the Slate Creek antimony deposit and vicinity.

[Field No. suffixes: D, soil; DS, site duplicate sediment; R, rock; S, stream sediment. CV, cold-vapor atomic absorption; EP, partial-extraction inductively coupled plasma atomic-emission spectrometry; ET, total-extraction inductively coupled plasma atomic-emission spectrometry; FA, fire-assay atomic absorption; HY, hydride-generation atomic absorption; PCT, percent; PPM, parts per million; Tot, total sulfur by Leco analyzer. Sources: DN, downstream from minesite; DS, distal from mineralized area; MINE, minesite; NM, naturally mineralized. Threshold, concentration above which content is considered anomalous in this study. FeOx, iron oxides; MnOx, manganese oxides; XRD, X-ray diffraction]

Field No.	Source	Sample description
98SC001R	NM	Colluvium; vein quartz with stibnite, pyrite, and possible arsenopyrite, in greenish-yellow-stained muscovite schist; fairly abundant sulfide-rich cobbles in colluvium; some sulfides are prismatic (probably stibnite).
98SC002R	NM	Outcrop; shattered, siliceous, muscovite-quartzite cut by thin quartz veins; FeOx and lesser MnOx on cleavage planes; possible disseminated pyrite in vein quartz; local thin graphitic schist.
98SC004R	NM	Outcrop; 3-ft-thick quartz-muscovite schist horizon in muscovite schist; cut along foliation by quartz veins; yellow-green staining and minor salts in protected areas suggest oxidized sulfides; graphite clots in quartz veins.
98SC008R1	MINE	Outcrop; quartz-muscovite-pyrite schist wallrock adjacent to mined-out pyrite-stibnite-quartz vein; from S. face; pyritic/silicified schist cut by numerous quartz veins/veinlets; pervasive yellow-green color from oxidizing sulfides.
98SC008R2	MINE	Outcrop; salts from protected areas on quartz-muscovite schist wallrock adjacent to mined-out pyrite-stibnite-quartz vein; XRD results are quartz, vanadate-barium muscovite, alunocopiapite [(Mg,Al)(Fe,Al) ₄ (SO ₄) ₆ (OH) ₂ ·20H ₂ O], hexahydrite (MgSO ₄ ·6H ₂ O), magnesiocopiapite [MgFe ₃ (SO ₄) ₆ (OH) ₂ ·20H ₂ O], biotite.
98SC010R	MINE	Mine waste; sulfide-rich mine waste around drainpipe; sample is pyrite-muscovite-quartz schist containing stibnite.
98SC011R	NM	Outcrop; old road switchback 30 ft above watersite; ferricrete, very FeOx-rich, and probably MnOx; ferricrete cements small angular clasts of muscovite schist.
98SC012R	MINE	Prospect waste; gray with fine stibnite in white to clear, highly sheared vein quartz; muscovite-rich; ferricrete cements muscovite schist fragments; local fresh pyrite; slickensides and shearing suggest fault.
98SC001S	NM	Sediment; low organic content; cobbles are FeOx stained; muscovite schist and quartzite dominant, minor vein quartz.
98SC002S	NM	Sediment; very fine, orange sediment in willow thicket; bog iron or mineralization(?); potential naturally mineralized sample; high organic content; FeOx sediment with sparse muscovite schist pebbles.
98SC003S	DS	Sediment; abundant moss/algae on rocks; moderate organic content; no FeOx staining; muscovite schist and quartzite dominant.
98SC004S	DN	Sediment; abundant FeOx-rich fine mud interstitial to boulders; low organic content; muscovite schist and quartz-muscovite schist dominant; minor vein quartz.
98SC005S	DS	Sediment; deeper gravel has a lot of FeOx in fines—very orange; low organic content; slight FeOx on surface cobbles; muscovite schist dominant, minor vein quartz.
98SC006S	DN	Sediment; fines to small boulders, all FeOx stained; sparse vegetation in active alluvial channel; no organic content; muscovite schist and quartzite dominant, minor vein quartz.
98SC007S	DN	Sediment; overbank cobbles appear to be less FeOx stained than those in active channel; no organic content; muscovite schist and quartzite dominant, vein quartz with pyrite and stibnite.
98SC007DS	DN	Sediment; duplicate of field No. 98SC007S.
98SC011D	NM	B-horizon soil; undisturbed tundra just above watersite; tan, micaceous, muddy, with dark-gray ferricrete; low organic content.
98SC012D	NM	B-horizon soil; undisturbed tundra just above prospect; tan, micaceous, with FeOx clots and platy quartz-muscovite fragments that look like sheared vein quartz with muscovite partings; low organic content.

Table 6. Descriptive and analytical data for sediment, rock, and soil samples collected from the Slate Creek antimony deposit and vicinity—Continued.

Field No.	Al_PCT_ET	As_PPM_HY	Au_PPM_FA	Ba_PPM_ET	Be_PPM_ET	Bi_PPM_ET	Ca_PCT_ET	Cd_PPM_EP	Ce_PPM_ET	Co_PPM_ET
Threshold	--	30	0.02	1,500	5	4	--	1	100	50
98SC001R	3.6	2,400	.032	210	<1	<10	.22	<.05	31	<2
98SC002R	3.8	77	.008	570	1	<10	.011	.16	32	4
98SC004R	6.8	8.3	.011	590	2	<10	.16	.38	57	10
98SC008R1	4.5	65	.011	700	1	<10	<.005	.06	44	<2
98SC008R2	4.2	120	.08	190	1	<10	.83	5	82	37
98SC010R	2.7	1,300	.025	300	<1	<10	.038	.17	27	<2
98SC011R	4.2	700	.021	640	2	<10	.016	.35	53	49
98SC012R	2.8	390	.034	420	1	<10	.016	1.2	26	21
98SC001S	7.4	830	.013	880	2	16	.52	.6	81	19
98SC002S	3.5	2,300	.021	740	1	<10	1.2	.76	40	230
98SC003S	7	60	.013	980	2	<10	1.2	1.9	71	17
98SC004S	5.9	1100	.028	630	2	11	.42	.93	62	28
98SC005S	7.3	440	.02	780	2	27	.55	4.1	96	20
98SC006S	6.1	1,500	.03	720	2	10	.4	.28	81	36
98SC007S	5.7	2,100	.041	710	2	10	.25	.09	84	10
98SC007DS	6	2,100	.035	700	2	<10	.23	<.05	91	12
98SC011D	12	56	<.005	1,300	3	12	.12	.21	110	11
98SC012D	8.1	63	.007	1,200	2	<10	.34	.12	86	6

Field No.	Cr_PPM_ET	Cu_PPM_EP	Fe_PCT_ET	Hg_PPM_CV	K_PCT_ET	La_PPM_ET	Li_PPM_ET	Mg_PCT_ET	Mn_PPM_ET	Mo_PPM_EP
Threshold	200	75	5	0.1	5	50	75	--	1,000	5
98SC001R	10	68	1.4	1.3	1.1	16	<2	.11	51	.6
98SC002R	9	8.3	1.6	.04	1.5	16	69	.16	240	.4
98SC004R	11	38	2.8	<.02	2	29	39	.41	300	.7
98SC008R1	3	5.8	1.1	.12	2	21	8	.19	17	.2
98SC008R2	17	69	4.9	.08	1.8	36	6	2.2	1,700	.2
98SC010R	5	30	1.5	.17	1	13	5	.11	33	.5
98SC011R	16	15	12	.13	1.4	24	42	.16	9,900	.8
98SC012R	4	18	6.5	.2	1.2	14	23	.12	6,700	.7
98SC001S	61	49	5.3	.13	2.5	46	36	.66	2,500	.7
98SC002S	29	22	21	.11	1.1	21	22	.39	29,000	1.3
98SC003S	42	33	3.7	.37	1.8	33	51	.89	2,600	--
98SC004S	32	35	5.4	.1	2	34	26	.57	2,300	.5
98SC005S	100	36	5.5	.1	2.2	46	42	.82	1,500	.7
98SC006S	37	37	6.9	.1	2.1	37	27	.58	2,100	.5
98SC007S	40	34	9.1	.12	2.3	42	18	.37	820	.6
98SC007DS	40	35	8	.31	2.3	44	19	.36	740	.6
98SC011D	110	37	5.5	.17	4	55	38	.74	760	1.2
98SC012D	74	26	4	.06	2.6	40	41	.54	550	2.3

Field No.	Na_PCT_ET	Nb_PPM_ET	Nd_PPM_ET	Ni_PPM_ET	P_PCT_ET	Pb_PPM_ET	S_Tot_PCT	Sb_PPM_HY	Sc_PPM_ET	Se_PPM_HY
Threshold	--	50	--	80	0.1	40	--	4	--	1.5
98SC001R	.038	<4	16	<3	.01	67	3.4	99,000	6	1.3
98SC002R	.071	5	16	10	.015	11	<.05	10	4	<2
98SC004R	1.1	10	27	30	.015	20	.21	4.6	9	.2
98SC008R1	.071	4	22	4	.005	32	.6	150	5	<2
98SC008R2	.071	7	48	100	.075	15	7	90	13	<2
98SC010R	.052	<4	14	4	.01	1,200	1.5	13,000	3	<2
98SC011R	.071	5	46	86	.035	18	<.05	53	5	<2
98SC012R	.052	<4	27	58	.02	120	.11	380	4	<2
98SC001S	.45	17	54	60	.08	34	.08	130	12	.3
98SC002S	.2	<4	60	430	.06	10	.07	450	5	.4
98SC003S	.98	13	42	56	.1	20	.06	12	12	2.1
98SC004S	.47	6	42	59	.055	40	.31	1,200	10	.2
98SC005S	.6	23	54	69	.09	34	.08	84	13	.2
98SC006S	.32	5	47	63	.05	43	.87	3,000	10	.2
98SC007S	.22	10	55	20	.05	50	.9	6,000	11	.3
98SC007DS	.23	10	57	23	.05	52	.78	5,200	10	<2
98SC011D	.28	21	63	30	.045	51	<.05	85	20	.4
98SC012D	.54	16	45	27	.095	68	.05	43	11	1.2

Field No.	Sn_PPM_ET	Sr_PPM_ET	Te_PPM_HY	Th_PPM_ET	Ti_PCT_ET	Tl_PPM_HY	V_PPM_ET	Y_PPM_ET	Yb_PPM_ET	Zn_PPM_ET
Threshold	10	--	0.05	20	--	--	100	50	--	150
98SC001R	<.5	55	.4	<6	.012	2.3	5	6	<1	270
98SC002R	<.5	36	<.1	11	.11	.5	30	4	<1	62
98SC004R	<.5	76	<.1	12	.19	.7	62	11	2	60
98SC008R1	<.5	53	<.1	6	.13	.9	34	4	<1	20
98SC008R2	<.5	68	<.1	40	.16	.8	37	27	4	420
98SC010R	<.5	31	<.1	<6	.05	.8	11	5	<1	21
98SC011R	7	39	.2	16	.11	.5	39	18	2	220
98SC012R	<.5	26	.2	<6	.08	.6	24	12	2	140
98SC001S	<.5	120	<.1	15	.43	.7	83	14	2	140
98SC002S	5	110	.2	16	.12	.4	50	15	2	280
98SC003S	<.5	170	<.1	10	.38	.6	110	17	2	190
98SC004S	<.5	91	.1	12	.35	.9	64	12	2	240
98SC005S	<.5	120	<.1	17	.62	.9	91	14	2	570
98SC006S	<.5	90	<.1	16	.31	<.1	65	13	2	160
98SC007S	<.5	84	.1	15	.22	.8	54	23	2	68
98SC007DS	<.5	87	<.1	16	.27	1	56	20	2	84
98SC011D	<.5	86	.1	23	.38	1.5	110	17	3	110
98SC012D	6	120	<.1	17	.33	1	110	10	2	170

lous contents of Co, Fe, and Ni and lower-level anomalous contents of Au, Bi, Hg, and Zn in naturally mineralized sediment; (3) lower-level anomalous contents of Bi, Ce, Fe, Hg, La, Pb, Th, and, possibly, V and Zn in naturally mineralized soils, and (4) lower-level anomalous contents of Au, Bi, Fe, Hg, Pb, and Zn in stream sediment downstream from the mine and mineralized area.

Dames & Moore (1992) collected one soil sample above and four soil samples within the disturbed mining area. Although their suite of element determinations was limited, they measured high As, Fe, and Pb contents in the soil collected above and high As, Cu, Fe, Ni, Pb, Sb, and Zn contents in one or more of four samples from the disturbed mining area. Hg was not detected, and Au, Bi, Co, and Mn were not determined, in their study.

Mine waste and mineralized outcrop within the disturbed mining area (field Nos. 98SC008R1, 98SC008R2, 98SC010R, 98SC012R, table 6) contained highly anomalous contents of As, Sb, Fe, and Pb and lower-level anomalous contents of Au, Cd, Hg, Mn, Ni, S, Th, Zn, and, possibly, Te. Colluvium and outcrop samples collected away from the disturbed mining area (field Nos. 98SC001R, 98SC002R, 98SC004R, 98SC011R, table 6) had elemental suites similar to those of the mine waste and mineralized outcrop at the minesite, with highly anomalous contents of As and Sb and lower-level anomalous contents of Au, Hg, Mn, Ni, Pb, Zn, and, possibly, Te.

Conclusions

The low pH values and predominance of sulfate in mine-related waters are due largely to the dissolution of pyrite and related chemical reactions, as described by Nordstrom and Alpers (1999). Stream waters downstream from the minesite are intermediate in composition with respect to bicarbonate and sulfate and have near-neutral pH values, which probably reflect mixing of bicarbonate-dominant, near-neutral pH waters with mineralized, acidic, sulfate-dominant waters. As mixing occurs and pH values rise, Fe oxide is deposited from the Fe-rich waters as flocs and coatings on alluvial cobbles, resulting in the conspicuous red-stained alluvial cobbles along most of the upper reach of Slate Creek (fig. 5). Metals mobile at low pH values, such as Al, As, Co, Cu, and Ni, are abundant in the mine-related waters but are quickly coprecipitated with the Fe oxide flocs and coatings upon mixing with bicarbonate waters. Concentrations of these species are continually building up over time in the Fe oxide flocs and coatings. Other abundant species in mine-related waters, such as Mn, Sb, SO_4^{2-} , and Zn, are still mobile at higher pH values and remain in solution downstream but in lower concentrations, owing to dilution.

Alkalinities in stream waters above and below the Slate Creek antimony deposit had a mean of 78 mg/L (as equivalent CaCO_3). The alkalinity at site 98SC007 (fig. 3), immediately below the mine wastepile and associated acidic mine drainage, was also 78 mg/L (fig. 5). Though not high, these alkalinities



Figure 5. Site 98SC007 (pH value, 6.9; conductivity, 260 $\mu\text{S}/\text{cm}$; total-dissolved-solids content, 246 mg/L) on Slate Creek immediately below the Slate Creek antimony deposit (see figs. 1, 3 for location). Red Fe oxide coatings on alluvial cobbles are common along much of lower Slate Creek. Mine wastepiles are visible in distance; Global Positioning System (GPS) unit in foreground for scale.

suggest that the streams still have the capacity to consume acid. Thus, if hydrologic conditions at the minesite change and the flow of acidic water is increased, the ecosystem should be able to consume some, if not all, of this acidic water. We note that precipitation and snowmelt would be the most likely causes of increased flow of acidic mine water and that corresponding flow increases would be expected for surrounding bicarbonate-dominant streams, a feature that would aid the natural reduction of acid and metal lodes in the water. The origin of the bicarbonate in the spring and stream waters could be calcium carbonate; however, no megascopic calcite was observed at the minesite or in the surrounding rocks. Accessory calcite may be present in the Precambrian metamorphic rocks. Alternatively, the bicarbonate and associated alkalinities could be derived from atmospheric CO₂ and produced by organic matter, as described in Hem (1985), or from reactions with accessory mafic minerals within the Precambrian metamorphic rocks, as described by Nesbitt and Jambor (1998) and Desborough and others (1998).

The naturally mineralized springs at site 98SC011 (fig. 6; located within the same mineralized zone as the mine but outside the disturbed mining area) and at site 98SC013 (at 1,800-ft [550 m] elevation, below the minesite but draining ground from the opposite side of the valley from the mine and wastepiles) probably provide conservative estimates for premining spring-water compositions at the minesite. With pH values of 5.6 and 7.7 and conductivities of 750 and 300 μS/cm, respectively, these springs indicate premining spring waters that

naturally ranged from acidic to neutral in pH value, had relatively high conductivities, had varying high TDS contents, were Fe rich, and were metalliferous. However, these naturally degraded waters were further degraded by historical mining activities in upper Slate Creek. The water presently flowing from the minesite has lower pH values, higher conductivities, and much higher metallic-ion contents relative to the naturally mineralized springs, as a result of several factors—surface disruption, concentration of sulfides (principally pyrite, but also arsenopyrite and stibnite) in mine wastepiles, particle-size reduction in the mine wastepiles relative to the solid bedrock from which they are derived (which exposes more sulfide surface area to weathering), and exposure of sulfides in the wastepile to oxidation processes. The original adits were long ago destroyed by weathering, structural failure, and subsequent surface-mining activities, but the collapsed openings presently provide conduits for ground-water passage through the mineralized bedrock into the mine wastepiles. The red-stained alluvial gravel along the upper reach of Slate Creek (see fig. 5) and the naturally mineralized Fe oxide-rich springs at the head of the Slate Creek basin (see fig. 6) were probably present before, and aided prospectors in, the discovery of the Slate Creek antimony deposit, although the extent of iron staining of alluvial cobbles along Slate Creek has been exacerbated by the historical mining activity.

Even though none of the sampled stream waters exceeded EPA aquatic-life standards, aquatic life along Slate Creek is



Figure 6. Site 98SC011 (pH value, 5.6; conductivity, 750 μS/cm; total-dissolved-solids content, 544 mg/L), showing natural spring within mineralized zone adjacent to the Slate Creek antimony deposit (see figs. 1, 3 for location). Extensive orange and red Fe oxide precipitates coat and cement together organic debris and mica schist colluvium.

evidently compromised because no algae were observed in the creekbed from the confluence with Eldorado Creek to the Slate Creek antimony deposit, a reach of nearly 2 mi (3.2 km). Qualitatively, the alluvium in Slate Creek was not at all “slippery,” as is commonly observed in streambeds with a healthy algal population, and sparse to no vegetation was growing in the active stream channel. In contrast, Eldorado Creek and the side drainages flowing into Slate Creek contained abundant algae, and active channels were well vegetated. EPA nonregulatory water-quality-guideline concentrations for Sb are 1,600 µg/L (freshwater chronic standard) and 9,000 µg/L (freshwater acute standard) (Environmental Protection Agency, 1980), 10 times larger than the highest value of 220 µg/L found in mine drainage in the present study (table 4). The EPA also states that “toxicity to algae can occur at concentrations as low as 610 µg/L” (Environmental Protection Agency, 1980). The stream waters along Slate Creek below the mine area range in Sb content from 100 to 190 µg/L (table 4). If the Sb content of stream waters is responsible for the absence of algae and vegetation along Slate Creek, then the above nonregulatory guidelines for antimony may be too high. Clearly, more work needs to be done along Slate Creek to determine the cause for the absence of algae and vegetation.

Stream-sediment, rock, and soil samples, both from sites affected by historical mining activities and from sites unaffected by mining, have highly anomalous As and Sb contents. Several other elements, including Au, Bi, Cd, Ce, Co, Fe, Hg, La, Mn, Ni, Pb, S, Th, and Zn, also are present in anomalous concentrations in one or more of these samples. The widespread presence of anomalous concentrations of this suite of elements in samples from the mineralized area, but outside the disturbed mining area, and in samples collected elsewhere in the Slate Creek drainage suggests that mineralized rocks (and the soils and sediment derived from them) are present beyond the known boundaries of the minesite, as demonstrated at site 98SC002, located upstream of the mine but approximately on strike with the mineralized vein system. The stream-sediment sample from this site had the highest As, Co, Fe, Mn, and Ni contents of all the stream-sediment samples, including those from just below the mine wastepiles, and also had high Sb contents. The orange-red, Fe-rich, fine sediment present at site 98SC002 is a metallic-ion sink that likely has been accumulating metals derived from upstream rocks and transported by spring and stream waters for thousands of years. Metalliferous ferricrete sampled from a spring at site 98SC011 (figs. 3, 5), and ferricrete deposits several feet thick observed in alluvium at several places downstream along Slate Creek, both indicate probable premining metallic-ion accumulations transported by Fe-rich spring and stream waters.

Anomalous Hg contents (0.1–1.3 ppm; mean, 0.25; $n=14$) were measured in 14 of the 18 stream-sediment, rock, and soil samples collected within and outside the minesite, and in sediment samples downstream from the mineralized area. The presence of anomalous Hg contents in stream sediment, rocks, and soils outside the mine area indicates that the mercury is natural and not anthropogenic. No mercury was detected in

water samples in this study or in Dames & Moore’s (1992) study (detection limits, 0.005 and 0.2 µg/L, respectively), suggesting that the mercury present in stream sediment, rocks, and soils occurs in a stable mineral phase under surficial conditions. Anomalous Hg contents are not uncommon in simple antimony deposits (Bliss and Orris, 1986), and the mineral phase is commonly cinnabar, a mercury sulfide mineral highly stable in the surficial environment (J.E. Gray, written commun., 1999). Thus, it is unlikely that mercury poses a threat to the aquatic environment.

Bundtzen (1981) listed several stibnite-quartz vein deposits within the Kantishna belt that appear to be similar to the Slate Creek antimony deposit, including the Stampede deposit, the largest antimony producer in the district. If, as appears likely, these vein deposits also contain pyrite, then acid-generation and mine-drainage waters similar to those at Slate Creek would be expected. The geochemical data from this study indicate that the stibnite-antimony vein system at the Slate Creek antimony deposit extends beyond the disturbed mining area, and demonstrate that naturally high concentrations of potentially toxic metals are present in the surrounding area. These environmental-geochemical features are not unique to the Slate Creek antimony deposit and should be considered before remediation efforts at other historical antimony deposits within the Kantishna belt.

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