U. S. DEPARTMENT OF THE INTERIOR
U. S. GEOLOGICAL SURVEY

Environmental Characteristics of the Abandoned Greenwood Mine Area, Prince William Forest Park, Virginia: Implications for Mercury Geochemistry

by

Robert R. Seal, II[1], David P. Haffner[1], and Allen L. Meier[2]

Open-File Report 98-326

[1]U.S. Geological Survey, 954 National Center, Reston, VA 20192
[2]U.S. Geological Survey, 973 Denver Federal Center, Denver, CO 80225

1998

TABLE OF CONTENTS

ABSTRACT

This report presents water quality data for samples collected in December, 1997 from the abandoned Greenwood mine area in Prince William Forest Park, Prince William County, Virginia. Data include temperature, pH, specific conductance, dissolved oxygen, alkalinity, flow, and total acid soluble and dissolved major and trace element concentrations for four sites around the mine workings. Data are interpreted in terms of their implications for the geochemical behavior of mercury.

SCOPE

The National Park Service acquired a 43-acre tract of land in Prince William County, Virginia for incorporation into Prince William Forest Park in July, 1997 (Fig. 1). The abandoned Greenwood gold mine site is located within the tract. The U. S. Geological Survey conducted reconnaissance sampling at the site in December, 1997 to: (1) assess water quality at the site; and (2) assess the environmental impact on the surrounding ecosystem. Also in December, 1997, the National Park Service collected six samples in a reconnaissance soil geochemical survey at the site. During this survey, the National Park Service identified Hg concentrations of over 40 mg/kg (C. Pollio, personal communication, 1998). Mercury amalgamation is known to have been used extensively in historic gold mining operations in the eastern United States (Callahan et al., 1994; Sweet, 1980).

The Greenwood mine is a gold property that is located in Prince William County at the northeastern end of the 175 km-long Virginia gold-pyrite belt, also known as the Virginia volcanic-plutonic belt (Pavlides et al., 1982). The Greenwood deposit is hosted by the Ordovician (approximately 475 million year old) Lake Jackson pluton. The Lake Jackson pluton is a metamorphosed tonalitic intrusion. Tonalites consist of subequal proportions of quartz and sodium- and calcium-rich feldspar. The gold deposits of the Virginia gold-pyrite belt are typically classified as low-sulfide gold-quartz deposits. This type of deposit generally consists of quartz veins with minor amounts of pyrite and gold (Goldfarb and others, 1995). Although exposures are poor, the Greenwood deposit probably conforms to this classification.

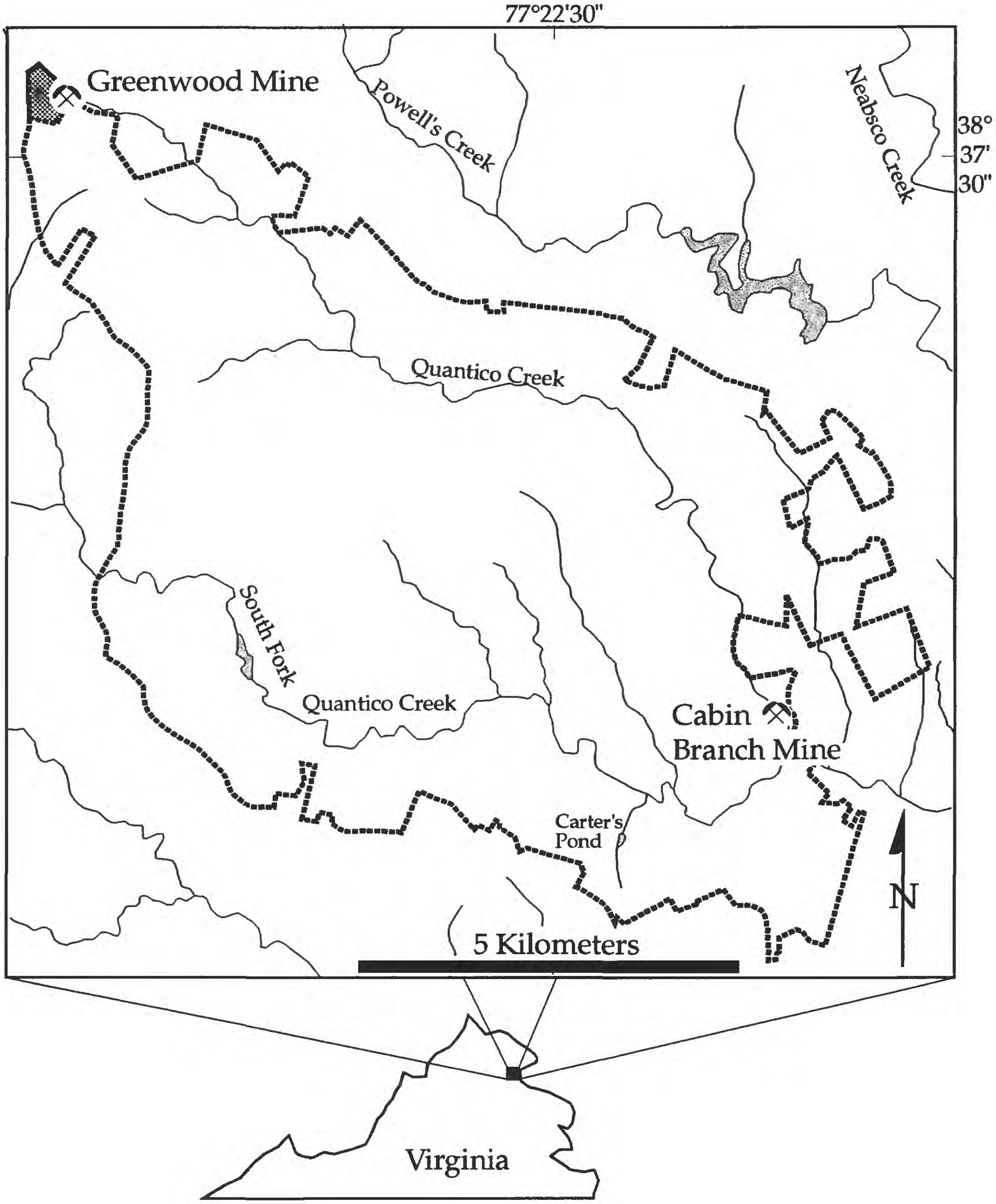

Figure 1: Map of Prince William Forest Park. Park boundary is shown as heavy dashed line. Streams are shown as thin solid lines. Ponds and lakes are shown as stippled patterns. The 43-acre tract containing the Greenwood site is shown as gray.

Reports in the published literature on the mine are scarce. Lonsdale (1927) reported that two vertical shafts were sunk, which are still identifiable. He also noted that the mine has been abandoned at least since 1907. The mine site is located at the headwaters of Quantico Creek, which flows past the reclaimed Cabin Branch mine, approximately 11 km downstream (Fig. 1). Elsewhere in Prince William County, Pardee and Park (1948) described placer operations at the Crawford property on Neabsco Creek and its tributaries, located approximately 10 km east of the Greenwood mine. The placer was worked around 1935 and a small amalgamation plate was used to extract the gold.

WATER QUALITY

Sample Sites

To date, four surface-water samples have been collected and analyzed from the Greenwood mine site in Prince William Forest Park (Fig. 2). These samples included water within shafts (2), a man-made pond upstream from the shafts, and the small stream (headwaters of Quantico Creek) that flows past the site. The stream sample was taken downstream of the shafts at the boundary of the 43-acre tract.

One shaft (PWGM-1-1) contained abundant organic debris (sticks, leaves, etc.) and the water in the shaft was dark brown and covered by an iridescent bacterial film. A distinct sulfurous odor was also noted. The other shaft (PWGM-4-1), north of the first along a shallow trench, was filled with light brown water with a less well developed bacterial film. A less distinct sulfurous odor was also noted.

At each site, two splits were collected for cation analysis; one split was unfiltered and the other split was filtered through a 0.45 µm filter. The collection of two splits was done to assess qualitatively the transport of heavy metals adsorbed on fine-grained suspended particulate matter. Field and laboratory procedures are summarized in Appendix 1. In the context of the Greenwood site, mercury (Hg) is notably absent from the suite of elements analyzed; future work should remedy this deficiency. Descriptions of the sampling sites are presented in Appendix 2.

Results

Complete analyses of all water samples are presented in Appendix 3. General characteristics of water quality are summarized in Table 1; salient features are highlighted below. The waters sampled from within the shaft depressions are considerably different from the pond and stream samples. The pH values of all samples were slightly acidic and ranged from 5.9 to 6.4. The specific conductance ranged from 112.3 to 311.0 µS/cm, which corresponds to an approximate range of total dissolved solids of 73 to 200 mg/L. All dissolved oxygen levels were well below saturation. Dissolved oxygen ranged from 5 to 7 mg/L for the stream and pond, respectively, which are approximately 39 to 57 % of saturation. Dissolved oxygen values for the waters in the shaft depressions were 0.02 and 0.9 mg/L, which are approximately 0.2 and 8 % of saturation, respectively. The low oxidation state of the waters from the shaft depressions is also reflected in the Fe^{2+}/Fe_{total} ratios, where the shaft waters have values between 0.75 and 0.85. In addition, there is a broad negative correlation between Fe^{2+}/Fe_{total} and dissolved oxygen (Fig. 3).

Dissolved sulfate values for the stream and pond average 16.5 mg/L, whereas the sulfate concentration of the shaft water at PWGM-1-1 was 0.38 mg/L and that at PWGM-4-1 was 69.0 mg/L. Total dissolved iron values are low in the stream and pond (<0.34 mg/L); the values from the water in the shaft depressions are higher (7.1 and 33.0 mg/L) and presumably reflect a combination of the greater solubility of reduced iron (Fe^{2+}) compared to oxidized iron (Fe^{3+}) and the greater solubilty of total iron due to complexation with dissolved organic carbon (DOC) compounds. The brown color of the shaft waters is consistent with high DOC. Dissolved aluminum (up to 0.29 mg/L), and total base metals (copper + zinc + nickel + cobalt + cadmium + lead; up to 0.05 mg/L) values are generally low compared to waters around the Cabin Branch mine site (Fig. 4). Alkalinity values range from 23.0 to

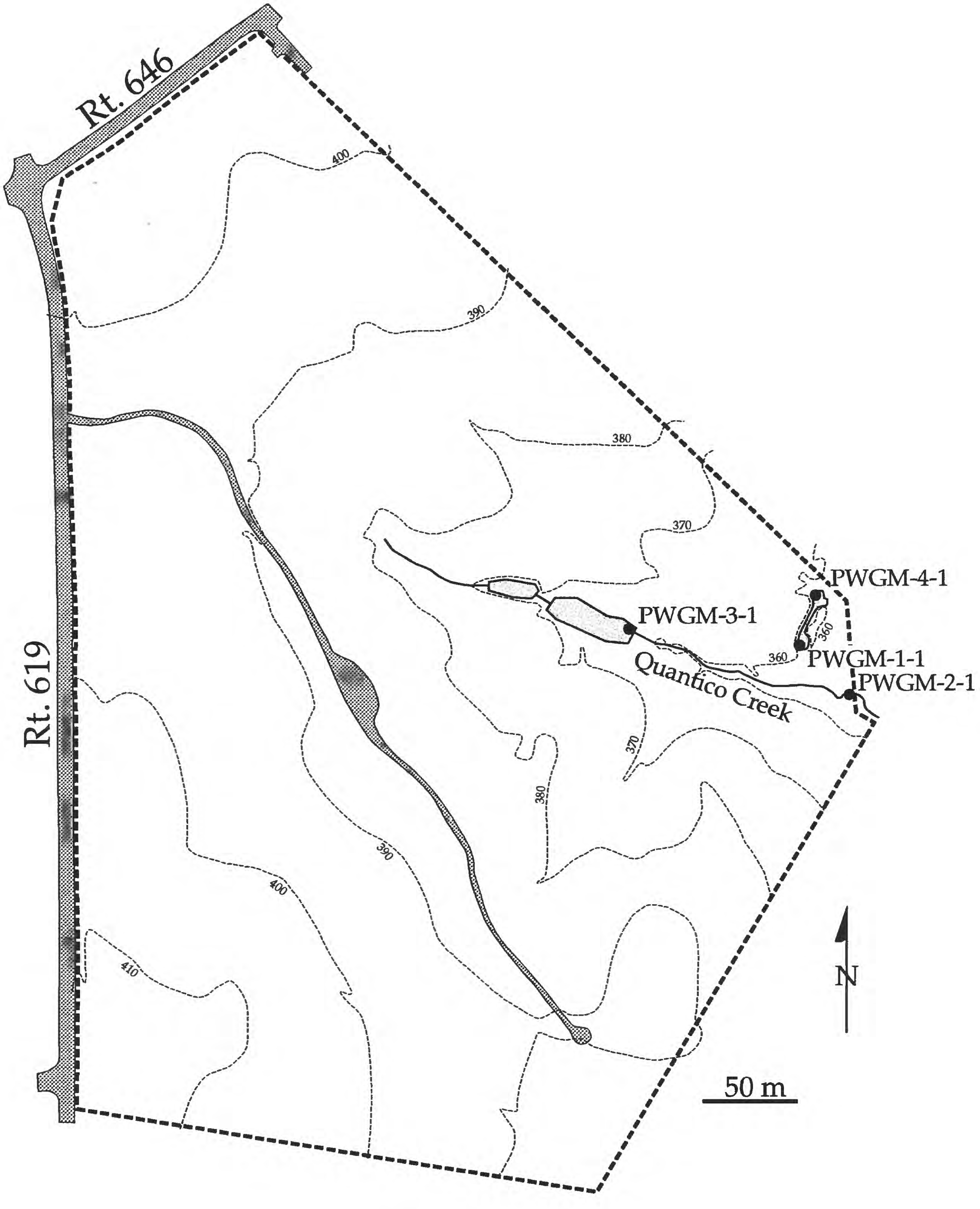

Figure 2: Map of 43-acre tract surrounding the abandoned Greenwood mine site. Tract boundary is shown as heavy dashed line. Topographic contours are shown as light dashed lines, in feet. Quantico Creek is shown by solid line. Roads are shown as dark stippled pattern and ponds are shown as light stippled pattern. Sample sites are labeled.

Table 1. Comparison of the Range of Selected Water Quality Parameters for Filtered Samples.

	Greenwood Shafts		Cabin Branch* Ground Waters		Cabin Branch* Seeps		Quantico Creek Greenwood Area		Quantico Creek* Cabin Branch Area	
	High	Low	High	Low	High	Low	High	Low	High	Low
pH	6.1	5.9	7.0	4.1	6.9	5.7	6.4	6.2	7.1	6.8
Specific Conductance µS/cm	311.0	155.0	2,050.0	433.0	1,550.0	557.0	198.7	112.3	138.7	60.0
Dissolved Oxygen mg/L	0.9	0.02	2.6	0.5	9.0	0.05	7.0	5.0	11.2	9.0
Alkalinity mg/L $CaCO_3$	69.8	36.2	209.4	0.0	201.6	1.2	29.2	23.0	17.5	13.0
SO_4 mg/L	69.0	0.38	1,200.0	200.0	790.0	260.0	17.0	16.0	41.0	10.0
Hardness mg/L $CaCO_3$	124.2	27.8	1,232.5	141.0	655.0	250.6	40.5	30.2	49.3	13.7
Fe µg/L	33,000.0	7,100.00	17,000.0	190.0	39,000.0	85.0	340.0	220.0	320.0	120.0
Al µg/L	290.0	220.0	5,500.0	<0.01	1,100.0	<0.01	180.0	45.0	68.0	4.3
Cu µg/L	8.0	0.7	3,300.0	3.0	1,300.0	1.0	3.0	2.0	10.0	0.8
Zn µg/L	27.0	3.0	11,000.0	36.0	13,000.0	390.0	41.0	5.0	330.0	0.8
Cd µg/L	0.1	<0.02	20.0	0.2	35.0	0.2	0.2	0.03	0.5	<0.02
Pb µg/L	8.3	0.4	12.0	<0.05	2.8	<0.05	0.3	0.2	0.2	0.07
Total Base Metals mg/L	0.046	0.014	14.434	0.058	14.446	0.452	0.047	0.008	0.343	0.002

*Cabin Branch data are from R.R. Seal, II, unpublished data, 1998.

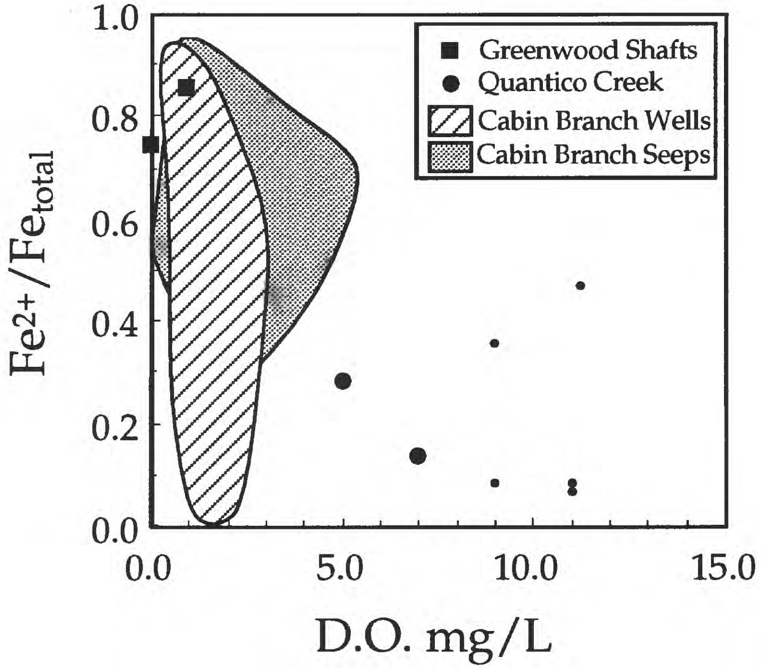

Figure 3: Plot of Fe^{2+}/Fe_{total} vs. dissolved oxygen (D.O.). Cabin Branch data are from R.R. Seal, II, unpublished data (1998). Quantico Creek data indicated by small circles are from the vicinity of the Cabin Branch mine and are from R.R. Seal, II, unpublished data (1998). Note that low oxidation states are represented by low D.O. levels and high Fe^{2+}/Fe_{total} values. The scatter of the Cabin Branch well data to low Fe^{2+}/Fe_{total} values at a fairly constant D.O. value indicates oxidation-reduction disequilibrium in the well waters.

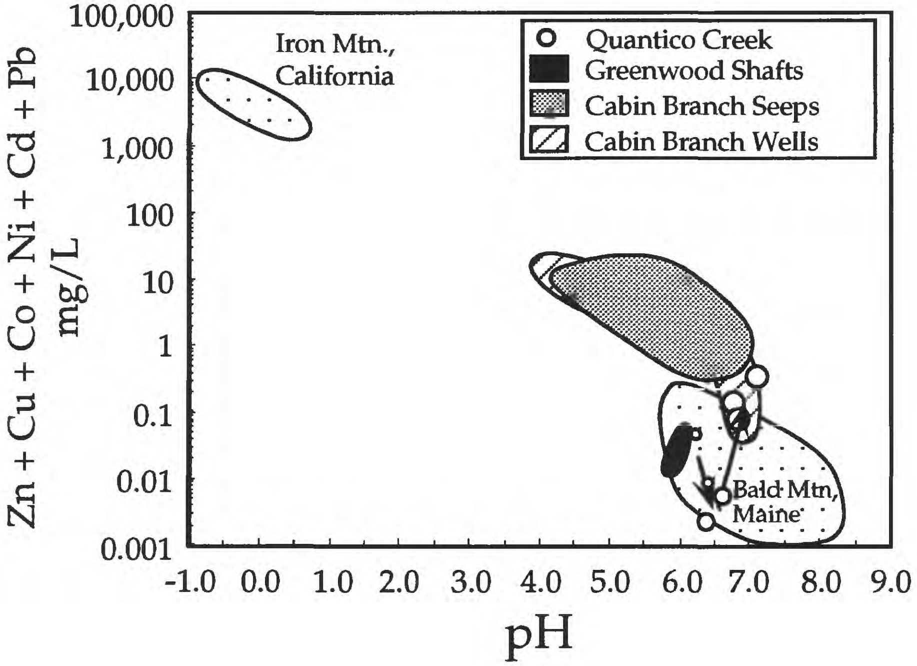

Figure 4: Plot of total base metals vs. pH. Increasing size of Quantico Creek Symbols and arrows qualitatively indicate distance downstream from headwaters. Medium sized symbols are for samples taken a short distance upstream of the Cabin Branch mine site; large symbols are for samples taken downstream of the Cabin Branch mine site. Cabin Branch data and Bald Mountain, Maine data are from R.R. Seal, II, unpublished data (1998). Iron Mountain, California data are from Alpers et al. (1994). Data from Iron Mountain and Bald Mountain are plotted for comparison purposes and represent the extremes of water quality values associated with massive sulfide deposits similar to the Cabin Branch mine. Iron Mountain is an U.S.E.P.A. Superfund site. Bald Mountain is an unmined deposit; thus, all water chemistry signatures represent natural background values.

69.8 mg/L $CaCO_3$ for all samples. Hardness values for all samples vary between 27.8 and 124.2 mg/L $CaCO_3$ equivalent.

Comparison with Water Quality Standards

The dissolved heavy metal concentrations of the Greenwood area waters are summarized in Table 2 and compared with U.S.E.P.A. (1996) water quality standards for acute effects (criterion maximum concentrations; CMC) in freshwater aquatic systems. For the heavy metals cadmium, chromium, copper, lead, nickel, silver, and zinc, the toxic effects decrease with increasing water hardness. For comparison purposes, CMC values for these metals are calculated for the low and high limits of water hardness values observed in the shaft depressions and are presented in Table 2. Heavy-metal water quality for all samples from the Greenwood area meet the U.S.E.P.A. (1996) standards with the exception of copper from sample PWGM-1-1 from the shaft depression. Here, the measured concentration was 8.0 µg/L, compared to the CMC of 5.1 µg/L.

Comparison with Other Gold Deposits

The environmental signatures of low-sulfide gold deposits, such as the Greenwood deposit, have been summarized by Goldfarb et al. (1995). For the class as a whole, the potential for adverse environmental impacts are considered minimal from a geologic perspective because the low sulfide and base-metal content is not likely to result in heavy-metal laden acid mine drainage. Furthermore, this type of deposit can be characterized by carbonate alteration which can naturally mitigate acid drainage. However, the greatest potential threat to environment comes from irresponsible mineral processing practices, chief among these for the Greenwood site is the use of mercury amalgamation to concentrate gold.

From a geologic perspective, the Greenwood waters are indistinguishable from other mine waters from low-sulfide gold deposits in terms of pH and dissolved base metal concentrations (Cieutat et al., 1994; Trainor et al., 1995; Fig. 5). Compared to waters around the reclaimed Cabin Branch pyrite mine, the Greenwood waters have much lower heavy-metal concentrations as would be expected from geologic considerations (Fig. 4).

IMPLICATIONS FOR MERCURY GEOCHEMISTRY

Anatomy of a Mercury Amalgamation Facility

Mercury amalgamation is a common technique that has been used in gold mining operations historically; it is also used today in less developed countries in South America, Asia, and Africa (Lacerda, 1997; Sweet, 1980). For small-scale operations, it offers the advantages of being cheap, reliable, and portable. Its wide-spread use has resulted in adverse environmental impacts; mercury poisoning related to gold mining has been reported in Brazil, China, and the Philippines (Lacerda, 1997). Pardee and Park (1948) reported the use of copper-plate mercury amalgamation around 1935 in Prince William County at the Crawford property east of the Greenwood site. Details of the mineral processing techniques at the Greenwood site are not available, but the use of copper-plate amalgamation at the nearby Crawford property suggests that the same process may have been used at Greenwood.

Mercury is used to separate fine gold particles through amalgamation in both placer and hard-rock mining operations. In hard-rock mining operations, the ore is first crushed, then the ore typically undergoes a gravimetric concentration step. The concentrate is then washed over mercury, or mercury amalgamated to a copper plate (generally 0.3 to 1.0 cm thick); the mercury readily alloys with gold. The alloy or amalgam is then typically roasted in open air to vaporize the more volatile mercury and leave the gold behind (Lacerda, 1997; Sweet, 1980). Interestingly, the high dissolved

Table 2. Comparison of Heavy Metal Concentrations of Greenwood Mine Site Filtered Water Samples with Regulatory Standards[1].

	PWGM-1-1 Shaft	PWGM-4-1 Shaft	PWGM-2-1 Quantico Creek	PWGM-3-1 Lower Pond	Low Freshwater CMC	High Freshwater CMC
Hardness (mg/L $CaCO_3$)	27.8	124.2	40.5	30.2	27.8	124.2
As (µg/L)	0.4	1.0	<0.2	<0.2	360.0	360.0
Cd[2] (µg/L)	0.1	<0.02	0.2	0.03	0.9	4.7
Cr[2,3] (µg/L)	<0.5	<0.5	<0.5	<0.5	192.3	655.3
Cu[2] (µg/L)	8.0	0.7	3.0	2.0	5.1	20.9
Pb[2] (µg/L)	8.3	0.4	0.2	0.3	15.6	81.7
Ni[2] (µg/L)	2.2	3.9	1.9	0.9	479.2	1700.2
Se (µg/L)	0.3	0.6	0.5	0.4	20.0	20.0
Ag[2] (µg/L)	<0.01	<0.01	<0.01	<0.01	0.4	5.0
Zn[2] (µg/L)	27.0	3.0	41.0	5.0	38.7	137.5

[1] Standards are U.S.E.P.A. Criterion Maximum Concentrations for acute toxicity in freshwater aquatic systems (U.S.E.P.A., 1996).

[2] CMC values for these elements vary as a function of the hardness of the water (see U.S.E.P.A., 1996). Low CMC values are calculated using the lowest observed hardness value; high CMC values are calculated using the highest observed hardness value.

[3] CMC values are for Cr (III).

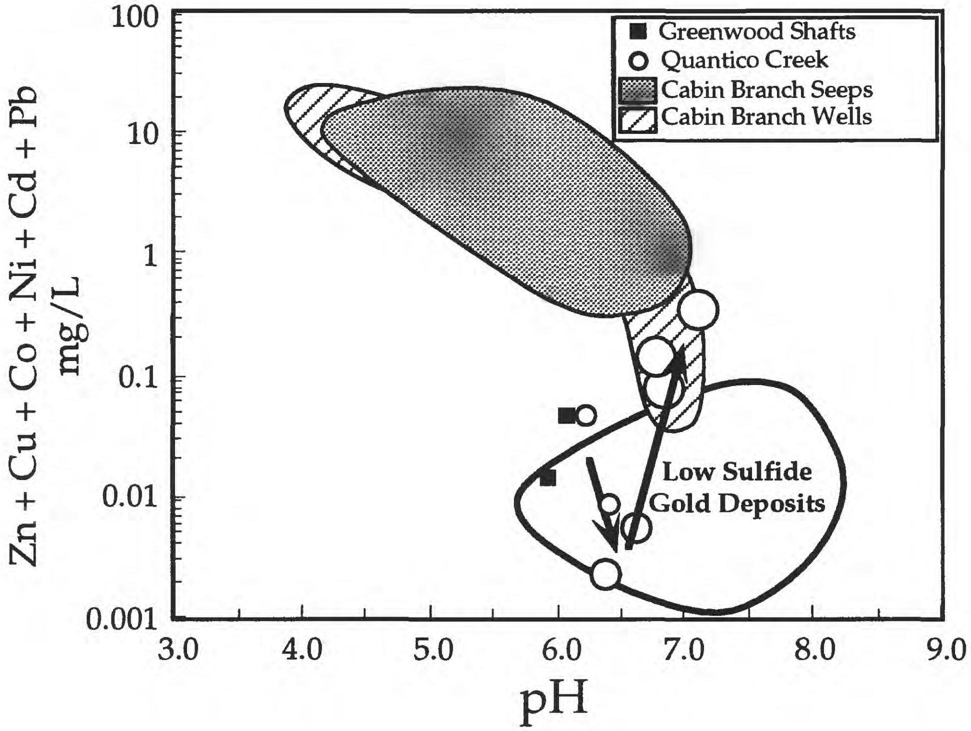

Figure 5: Plot of total base metals vs. pH. Increasing size of Quantico Creek symbols and arrows qualitatively indicate distance downstream from headwaters. Medium sized symbols are for samples taken a short distance upstream of the Cabin Branch mine site; large symbols are for samples taken downstream of the Cabin Branch mine site. Cabin Branch data are from R.R. Seal, II, unpublished data (1998). Field for low-sulfide gold deposits is defined by data from Cieutat et al. (1994), Goldfarb et al. (1995), and Trainor et al. (1995).

copper concentrations in sample PWGM-1-1 may be a reflection of the undocumented use of the copper-plate amalgamation process at the Greenwood site.

Contamination of the environment with mercury occurs during at least three stages of the process. First, some mercury is released in the water that is used to wash the ore concentrate over the mercury or copper-mercury plate. Second, some mercury adheres to the processed ore and is disposed of on site as solid mine waste. Third, mercury is released to the atmosphere during the roasting of the amalgam. Thus, at the abandoned Greenwood site, the greatest potential modern threat from mercury used in historic mining operations comes from the solid mine wastes that may have been disturbed around the site.

Geochemistry of Mercury

Dissolved mercury can be found in several forms in nature including elemental mercury (Hg°), inorganic free mercury (Hg^{2+}), inorganically complexed mercury, organically complexed mercury, and methylmercury (CH_3Hg^+), among others. Of these species, methylmercury is the most hazardous because it is a neurotoxin, which tends to biomagnify in the food chain in aquatic systems.

Several factors tend to enhance mercury methylation in freshwater aquatic systems; these factors include pH, and concentrations of dissolved organic carbon (DOC), oxygen, and sulfate (Gilmour and Henry, 1991). The significance of these factors in mercury methylation are related to their effects on sulfate-reducing bacteria, such as *Desulfovibrio desulfuricans*, which are the principal methylators of mercury in aquatic systems (Compeau and Bartha, 1985; Gilmour and Henry, 1991; Gilmour et al., 1992). In general terms, the metabolic processes of sulfate-reducing bacteria consume sulfate and organic compounds to produce hydrogen sulfide and carbon dioxide; methyl complexes which can combine with mercury are a byproduct of this process. Thus, sulfate-reducing bacteria tend to thrive in environments that are low in dissolved oxygen, and high in sulfate and organic matter. However, in terms of enhanced methylation of mercury, these factors have competing effects. At low sulfate concentrations, mercury methylation is inhibited because the metabolism of sulfate-reducing bacteria is limited by sulfate availability; at high concentrations, excessive sulfide product can sequester mercury from methylation through the formation of mercury sulfide (Gilmour and Henry, 1991). Gilmour and Henry (1991) suggested that the optimum range of sulfate concentrations for maximum mercury methylation is between approximately 20 and 50 mg/L. Research in the Florida Everglades suggests that the optimum range of sulfate concentrations might be lower, from approximately 2 to 20 mg/L (W. Orem, written communication, 1998). Likewise, organic matter is essential to the metabolism of sulfate-reducing bacteria, and is abundant in the shaft depressions.

In the case of the Greenwood site, the environment documented in the shaft depressions is conducive to mercury methylation: dissolved oxygen levels are low, and organic matter is abundant. The distinct hydrogen sulfide odor noted at PWGM-1-1 and PWGM-4-1 indicates that sulfate-reduction is actively occurring. At PWGM-1-1, the sulfate concentration is abnormally low (0.38 mg/L) compared to the stream and pond values (16.0 and 17.0 mg/L, respectively) and may indicate that the system became sulfate-limited. In contrast, the sulfate concentration at PWGM-4-1 (69.0 mg/L) was higher than the surrounding stream and pond values. The dissolved oxygen concentration at PWGM-4-1 (0.9) was also higher than PWGM-1-1 (0.02) and may suggest that the elevated sulfate concentrations are due to secondary oxidation of hydrogen sulfide. Therefore, the potential for significant mercury methylation in the shaft depressions is significant.

CONCLUSIONS AND RECOMMENDATIONS

With the exception of copper in PWGM-1-1, the concentrations of heavy metals meet water quality standards for freshwater aquatic systems. The pH and heavy metal values from the Greenwood area are very similar to those for other low-sulfide gold deposits. Thus, acidity and heavy metals appear to pose no significant environmental threat around the abandoned mine site. However, the case for mercury may be different.

Dissolved mercury concentrations were not measured in the present study. However, significant mercury concentrations would not be surprising considering the high mercury level reported in soils around the site by the National Park Service, and the fact that mercury amalgamation historically was an important gold processing technique. Furthermore, the geochemical environment defined for the shaft depressions on the property is condicive to the production of methylmercury, the most toxic species of mercury in aquatic systems.

Future work at the site, and downstream, should evaluate the speciation of dissolved mercury to determine methylmercury concentrations. Mercury concentrations of fish (whole-body and (or) liver) at the site and downstream may be useful in determining the extent of contamination. Assuming that the mercury contamination is due to mercury amalgamation used in gold recovery, then long-term problems may be associated with residual mercury in solid mine wastes around the site. To assess the nature and extent of the problem, soil sampling survey on a grid around the site should be conducted to determine the mineralogy and geochemistry of the soils.

ACKNOWLEDGMENTS

The cooperation and assistance of Carol Pollio and Ann Brazinski of the National Park Service is greatly appreciated. Gregory Wandless assisted in the water sampling.

REFERENCES

Alpers, C.N., Nordstrom, D.K., and Thompson, J.M., 1994, Seasonal variations of Zn/Cu ratios in acid mine water from Iron Mountain, California: in Environmental Geochemistry of Sulfide Oxidation, C.N. Alpers and D.W. Blowes, eds., Amer. Chem. Soc. Symposium Series 550, p. 324-344.

Callahan, J.E., Miller, J.W., and Craig, J.R., 1994, Mercury pollution as a result of gold extraction in North Carolina, U.S.A.: Applied Geochemistry, v. 9, p. 235-241.

Cieutat, B.A., Goldfarb, R.J., Borden, J.C., McHugh, J., and Taylor, C.D., 1994, Environmental geochemistry of mesothermal gold deposits, Kenai Fjords National Park, south-central Alaska, *in* Till, A.B., and Moore, T., eds., Geological Studies in Alaska by the U.S. Geological Survey, 1993: U.S. Geological Survey Bulletin 2107, p. 21-25.

Compeau, G.C., and Bartha, R., 1985, Sulfate-reducing bacteria: principal methylators of mercury in anoxic estuarine sediments: Applied and Environmental Microbiology, v. 50, p. 498-502.

Gilmour, C.C., and Henry, E.A., 1991, Mercury methylation in aquatic systems affected by acid deposition: Environmental Pollution, v. 71, p. 131-169.

Gilmour, C.C., Henry, E.A., and Mitchell, R,., 1992, Sulfate stimulation of mercury methylation in freshwater sediments: Environmental Science and Technology, v. 26, p. 2281-2287.

Goldfarb, R.J., Berger, B.R., Klein, T.L., Pickthorn, W.J., and Klein, D.P., 1995, Low sulfide Au quartz deposits: U.S. Geological Survey Open-File Report OF95-831, p. 261-267.

Lacerda, L.D., 1997, Global mercury emissions from gold and silver mining: Water, Air, and Soil Pollution, v. 97, p. 209-221.

Lonsdale, J.T., 1927, Geology of the gold-pyrite belt of the northeastern Piedmont, Virginia: Virginia Geological Survey, Bulletin 30, 110 p.

Pardee, J.T., and Park, C.F., Jr., 1948, Gold deposits of the southern Piedmont: U.S. Geological Survey Professional Paper 213, 156 p.

Pavlides, L., Gair, J.E., and Cranford, S.L., 1982, Central Virginia volcanic-plutonic belt as host for massive sulfide deposits: Economic Geology, v. 77, p. 233-272.

Sweet, P.C., 1980, Processes of gold recovery in Virginia: Virginia Minerals, v. 26, no. 3, p. 29-33.

Trainor, T.P., Fleisher, S., Wildeman, T.R., Goldfarb, R.J., and Huber, C.S., 1995, Environmental geochemistry of the McKinley Lake gold mining district, Chugach National Forest, Alaska: U.S. Geological Survey Bulletin 2152, p. 47-57.

U.S. Environmental Protection Agency, 1996, Water quality standards, Federally promulgated water quality standards: Federal Register, 40 CFR Part 131, p. 611-640.

APPENDIX 1: FIELD AND ANALYTICAL METHODS

Water samples were collected in one-liter high-density polyethylene bottles that were doubly-rinsed with sample water prior to collection. Samples were divided into four splits for chemical analysis: two for cation analysis, one for anion analysis, and one for alkalinity determination. The cations splits included filtered (dissolved) and unfiltered (total acid soluble) aliquots. Samples were filtered through 0.45 µm nitrocellulose filters. Cation splits were stored at ambient temperature in acid-washed (10 % HCl) high-density polyethylene bottles and preserved with 1 drop of ultra-pure nitric acid per each 10 ml of sample. Anion and alkalinity splits were stored high-density polyethylene bottles that were not acid-washed and were refrigerated until the time that they were analyzed.

On-site measurements at the time of collection included air temperature, water temperature, pH, specific conductance, dissolved oxygen, dissolved ferrous iron, dissolved total iron, dissolved sulfate, dissolved nitrate, and water flow. The pH was measured using an Orion 230A pH meter with a 91-07probe, calibrated with pH = 4.00 and 7.00 buffer solutions. Specific conductance was measured with an Orion 135 specific conductance meter. Dissolved oxygen concentrations were determined with Chemetrix high-range ampoules or with an Orion 250A meter with an Orion 97-08-99 oxygen electrode. Dissolved total iron, ferrous iron, sulfate, and nitrate concentrations were determined in the field using a Hach DR2000 spectrophotometer. Alkalinity samples were analyzed by Gran titration with 0.18 N H_2SO_4.

Cations were analyzed at U.S. Geological Survey (Central Mineral Resources Team) laboratories in Denver, CO by inductively-coupled plasma mass spectrometry (ICP-MS). Anions were analyzed at U.S. Geological Survey (Water Resources Division) laboratories in Ocala, FL by ion chromatography (chloride, and sulfate) and by ion-selective electrode (fluoride).

APPENDIX 2: DESCRIPTIONS OF SAMPLE SITES

PWGM-1-1 (NPS GM002): 38° 37.8' N, 77° 26.0' W; Water in main mine shaft at Greenwood Mine; deep brown color and iridescent bacterial film on surface; abundant organic debris in water; sulfurous odor.

PWGM-2-1: 38° 37.8' N, 77° 26.0' W; Quantico Creek downstream from Greenwood Mine area; water had clear appearance and no odor; flow rate = 0.3 L/min.

PWGM-3-1: 38° 37.9' N, 77° 26.8' W; Lower pond upstream from Greenwood Mine area.

PWGM-4-1 (NPS GM001): 38° 37.9' N, 77° 26.0' W; Water in small mine shaft north of main shaft; brown color, less distinct sulfurous odor compared to PWGM-1-1, and abundant leaves.

APPENDIX 3: WATER-QUALITY DATA

SAMPLE NUMBER	**PWGM-1-1**	**PWGM-2-1**	**PWGM-3-1**	**PWGM-4-1**
Description	Shaft	Stream	Pond	Shaft
NPS Location	GM002			GM001
Collection Date	12/8/97	12/8/97	12/8/97	12/8/97
Field Parameters				
Air Temperature °C	6.6	6.6	6.5	6.8
Water Temperature °C	5.2	4.6	5.9	7.6
pH	6.1	6.2	6.4	5.9
Conductivity µS/cm	155	198.7	112.3	311
Dissolved O_2 mg/L	0.02	5	7	0.9
Dissolved (<0.45 µm) Concentrations				
Alkalinity mg/L $CaCO_3$	36.2	29.2	23	69.8
NO_3 mg/L	0	1.5	2.6	4.6
SO_4 mg/L	0.38	16	17	69
F mg/L	< 0.1	< 0.1	< 0.1	0.1
Cl mg/L	1.5	32	7.4	7.2
Hardness mg/L $CaCO_3$	27.8	40.5	30.2	124.2
Li µg/L	0.6	0.5	0.5	3.0
Be µg/L	0.05	< 0.05	< 0.05	0.2
Na mg/L	1.7	24	12	24
Mg mg/L	1.9	3.9	2.8	12
Al µg/L	290	45	180	220
SiO_2 mg/L	14	19	12	43
P µg/L	550	51	52	370
K µg/L	2100	1800	1300	1600
Ca mg/L	8.0	9.8	7.5	30
Sc µg/L	0.5	< 0.1	< 0.1	12
Ti µg/L	1.1	0.2	1.3	1.3
V µg/L	0.6	< 0.1	< 0.1	4
Cr µg/L	< 0.5	< 0.5	< 0.5	< 0.5
Mn µg/L	720	99	120	260
Fe mg/L	33.000	0.220	0.340	7.100
Fe^{2+} mg/L	22.4	0.07	0.05	8.3
Co µg/L	0.64	0.3	0.2	5.8
Ni µg/L	2.2	1.9	0.9	3.9
Cu µg/L	8	3	2	0.7
Zn µg/L	27	41	5	3
Cd µg/L	0.1	0.2	0.03	< 0.02
Pb µg/L	8.3	0.2	0.3	0.4
Ga µg/L	0.03	< 0.02	< 0.02	< 0.02
Ge µg/L	0.04	< 0.02	< 0.02	< 0.02
As µg/L	0.4	< 0.2	< 0.2	1
Se µg/L	0.3	0.5	0.4	0.6
Rb µg/L	3.3	1.5	1.1	1.5
Sr µg/L	54	57	41	170
Y µg/L	1.3	0.2	0.4	0.73
Zr µg/L	0.1	< 0.05	0.07	< 0.05

SAMPLE NUMBER	**PWGM-1-1**	**PWGM-2-1**	**PWGM-3-1**	**PWGM-4-1**
Dissolved (<0.45 µm) Concentrations (cont.)				
Nb µg/L	< 0.02	< 0.02	< 0.02	< 0.02
Mo µg/L	0.1	0.07	0.07	0.4
Ag µg/L	< 0.01	< 0.01	< 0.01	< 0.01
In µg/L	< 0.01	< 0.01	< 0.01	< 0.01
Sn µg/L	1	< 0.05	< 0.05	< 0.05
Sb µg/L	0.2	0.1	0.2	0.09
Te µg/L	< 0.1	< 0.1	< 0.1	< 0.1
Cs µg/L	< 0.01	< 0.01	< 0.01	< 0.01
Ba µg/L	49	31	22	32
La µg/L	1.6	0.2	0.3	0.75
Ce µg/L	3.6	0.4	0.63	2.0
Pr µg/L	0.48	0.05	0.09	0.2
Nd µg/L	2.0	0.23	0.38	0.75
Sm µg/L	0.38	0.04	0.06	0.1
Eu µg/L	0.061	0.01	0.02	0.03
Tb µg/L	0.04	0.006	0.01	0.02
Gd µg/L	0.35	0.060	0.091	0.13
Dy µg/L	0.24	0.050	0.052	0.14
Ho µg/L	0.053	0.008	0.02	0.03
Er µg/L	0.12	0.02	0.04	0.072
Tm µg/L	0.02	< 0.005	< 0.005	0.008
Yb µg/L	0.1	0.03	0.03	0.08
Hf µg/L	< 0.05	< 0.05	< 0.05	< 0.05
Ta µg/L	< 0.02	< 0.02	< 0.02	< 0.02
W µg/L	0.04	0.02	0.05	0.03
Re µg/L	< 0.02	< 0.02	< 0.02	< 0.02
Au µg/L	< 0.01	0.02	< 0.01	0.03
Tl µg/L	< 0.05	< 0.05	< 0.05	< 0.05
Bi µg/L	0.02	< 0.01	< 0.01	< 0.01
Th µg/L	0.62	0.03	0.10	0.15
U µg/L	0.05	0.03	0.06	0.14
Total Acid Soluble Concentrations				
Li µg/L	0.6	0.7	0.5	2.9
Be µg/L	0.05	< 0.05	0.08	0.2
Na mg/L	1.7	24	12	22
Mg mg/L	1.9	3.9	2.9	9.6
Al µg/L	290	91	300	370
SiO2 mg/L	14	19	12	42
P µg/L	730	62	69	450
K µg/L	2100	1700	1300	1500
Ca mg/L	8.0	9.9	7.5	30
Sc µg/L	< 0.1	0.3	< 0.1	15
Ti µg/L	1.1	0.1	0.9	2.7
V µg/L	0.7	< 0.1	4	4
Cr µg/L	< 0.5	< 0.5	< 0.5	< 0.5
Mn µg/L	730	100	180	250

SAMPLE NUMBER	**PWGM-1-1**	**PWGM-2-1**	**PWGM-3-1**	**PWGM-4-1**
Total Acid Soluble Concentrations (cont.)				
Fe mg/L	34.0	0.420	0.620	7.100
Co µg/L	0.63	0.3	0.3	5.6
Ni µg/L	2.2	1.8	0.8	3.8
Cu µg/L	13	2	2	1
Zn µg/L	52	40	5	20
Cd µg/L	0.2	0.08	0.03	0.04
Pb µg/L	14	0.4	0.61	0.76
Ga µg/L	0.04	< 0.02	0.02	0.03
Ge µg/L	0.04	< 0.02	< 0.02	0.02
As µg/L	0.5	< 0.2	< 0.2	2
Se µg/L	0.5	0.3	0.4	0.3
Rb µg/L	3.3	1.5	1.2	1.6
Sr µg/L	54	57	40	170
Y µg/L	1.3	0.3	0.54	0.76
Zr µg/L	0.05	< 0.05	0.06	0.07
Nb µg/L	< 0.02	< 0.02	< 0.02	0.02
Mo µg/L	0.1	0.08	0.08	0.4
Ag µg/L	< 0.01	< 0.01	< 0.01	< 0.01
In µg/L	< 0.01	< 0.01	< 0.01	< 0.01
Sn µg/L	1	< 0.05	< 0.05	< 0.05
Sb µg/L	0.2	0.07	0.06	0.04
Te µg/L	< 0.1	< 0.1	< 0.1	< 0.1
Cs µg/L	< 0.01	< 0.01	< 0.01	< 0.01
Ba µg/L	50	31	24	32
La µg/L	1.7	0.3	0.62	0.81
Ce µg/L	3.8	0.58	1.2	2.1
Pr µg/L	0.51	0.08	0.2	0.20
Nd µg/L	2.1	0.33	0.61	0.81
Sm µg/L	0.37	0.06	0.1	0.2
Eu µg/L	0.056	0.01	0.03	0.03
Tb µg/L	0.050	0.008	0.02	0.02
Gd µg/L	0.36	0.060	0.12	0.16
Dy µg/L	0.26	0.050	0.097	0.13
Ho µg/L	0.05	0.007	0.02	0.03
Er µg/L	0.14	0.03	0.050	0.070
Tm µg/L	0.02	< 0.005	0.008	0.01
Yb µg/L	0.1	0.03	0.06	0.06
Hf µg/L	< 0.05	< 0.05	< 0.05	< 0.05
Ta µg/L	< 0.02	< 0.02	< 0.02	< 0.02
W µg/L	0.06	0.02	0.09	0.05
Re µg/L	< 0.02	< 0.02	< 0.02	< 0.02
Au µg/L	0.02	< 0.01	< 0.01	0.07
Tl µg/L	< 0.05	< 0.05	< 0.05	< 0.05
Bi µg/L	0.02	< 0.01	< 0.01	< 0.01
Th µg/L	0.57	0.04	0.07	0.20
U µg/L	0.05	0.03	0.06	0.14