

Landscape Geochemistry Near Mineralized Areas of Eastern Alaska

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Chapter H of

**Recent U.S. Geological Survey Studies in the Tintina Gold Province,
Alaska, United States, and Yukon, Canada—Results of a 5-Year
Project**

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Abstract

The Pogo lode gold deposit was discovered in eastern Alaska in the early 1990s and provided the opportunity to study elemental distribution and mobility in the natural environment prior to mine development. Studying mineralized systems prior to mining allows us to compare the natural biogeochemical signature in mineralized versus nonmineralized areas. The resultant data and interpretation also provide a baseline for evaluating what, if any, changes in elemental distribution result from development. This report investigates the chemistry of stream water, streambed sediment, and soil in the context of regional bedrock geology. The major-ion chemistry of the waters reflects a rock-dominated aqueous system, and the waters are classified as Ca^{2+} and Mg^{2+} - HCO_3^- to Ca^{2+} and Mg^{2+} - SO_4^{2-} waters. Creeks draining the gneissic lithologies tend to be more sulfate dominated than those draining the intrusive units. Sulfate also dominated creeks draining mineralized areas; however, the underlying paragneiss unit could be contributing substantially to the sulfate concentration, and the sulfate concentration in these creeks may reflect a complex batholith-paragneiss boundary rather than mineralization. Arsenic concentrations in bed sediments were elevated in mineralized areas relative to nonmineralized areas. Elevated concentrations of nickel, chromium, iron, manganese, and cobalt appear to reflect the presence of ultramafic rocks in the drainage. In general, aqueous metal concentrations were below the State of Alaska's Aquatic Life Criteria and Drinking Water Standards, with the exception of arsenic in stream water, which ranged in concentration from less than 1 to 14 micrograms per liter ($\mu\text{g/L}$) and exceeded the drinking water standard at one site. The arsenic and antimony concentration in the A, B, and C soil horizons ranged from 3 to 410 milligrams per kilogram (mg/kg), 6.1 to 440 mg/kg, and 2 to 300 mg/kg, respectively,

for arsenic and 0.4 to 24 mg/kg, 0.6 to 25 mg/kg, and 0.2 to 16 mg/kg, respectively, for antimony. The arsenic and antimony concentrations in stream waters correlate well with the concentrations in soils. However, significantly less arsenic and antimony was extracted from C horizon soils in water leaching experiments, indicating that the arsenic and antimony in the C horizon is present in a less available form than in the A or B horizons. Arsenic and antimony uptake by grayleaf willow (*Salix glauca* L.) appears minimal, with arsenic concentrations ranging from less than 0.01 to 0.14 mg/kg and antimony concentrations ranging from less than 0.003 to 0.23 mg/kg in willow leaves. In general, the highest concentrations of both arsenic and antimony in water and soils were found near mineralized areas. Elevated arsenic concentrations were also found in bed sediments from mineralized areas. In these sample matrices, the presence of arsenic and (or) antimony was a good indicator of contact with mineralized rock units.

Introduction

The Pogo vein gold deposit was discovered in the early 1990s (Smith and others, 1999). Because our work was implemented before the mine was developed, we were able to study elemental distribution and mobility in the natural, undisturbed environment. The Tintina Gold Province (TGP) study area is located in the subarctic boreal forest of east-central Alaska (fig. H1; see fig. 1 of the Editors' Preface and Overview). The Pogo gold deposit, as well as other mineralized localities, is located within the study area. In 1999, we had the opportunity to compare the effect of the Pogo deposit mineralization type and other area mineralization on the soil, sediment, and water geochemistry relative to nonmineralized areas prior to active mining. Studying mineralized systems prior to mine development allows us to investigate the natural hydrogeochemical and biogeochemical signatures in mineralized versus nonmineralized areas. The resultant data and interpretation also provide a baseline for evaluating what, if any, changes in elemental distribution result from mineral development. Our goals were (1) to define geochemical

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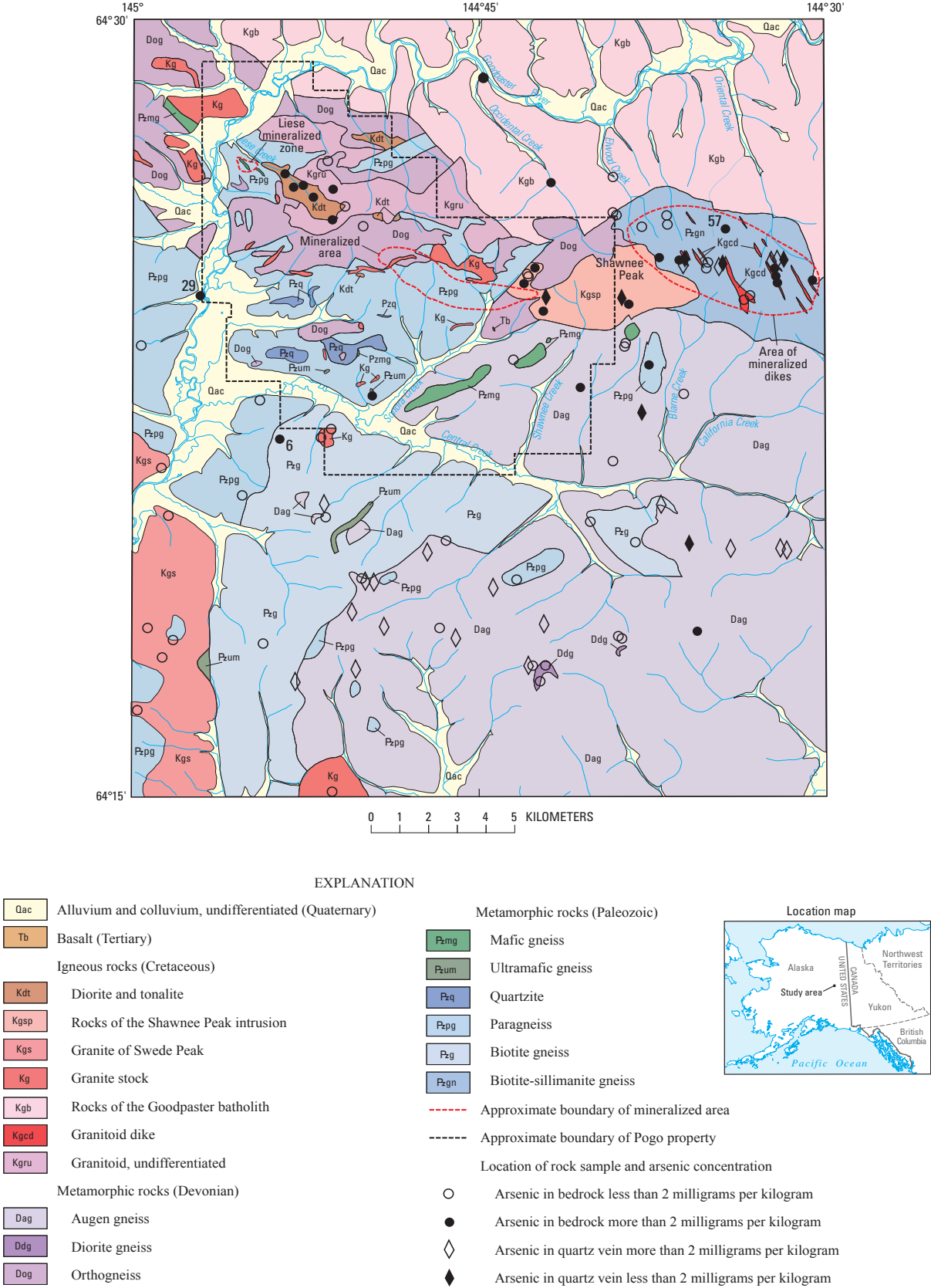


Figure H1. Site locations, simplified regional geology, and arsenic concentrations in bedrock and quartz veins, Pogo deposit region, eastern Alaska.

signatures imparted to the aqueous, soil, and biogeochemical environments from geologic (mineralized and nonmineralized) substrates, and (2) to provide a predevelopment snapshot of the geochemical signatures in selected drainages.

The Yukon-Tanana Upland has a continental climate with cold winters and warm summers and low to moderate annual precipitation (Gough and others, 2005). The area is characterized by heavily vegetated mountain drainages with alpine tundra and rounded barren peaks at higher elevation. The small river drainages are densely vegetated with alder and willow, whereas the larger rivers, such as the Goodpaster River and Central Creek, have broad meandering channels with forested banks and numerous sandbars. Boreal forest vegetation of the region is composed of closed spruce-hardwood subarctic forest containing white and black spruce, paper birch, aspen, and balsam poplar. Alpine tundra of the region is composed of low shrubs (willow, birch, spirea, and high bush cranberry) and a ground cover of forbs, mosses, and lichens.

The area soils are classified primarily as Cryepts (Inceptisols) and Orthels (Gelisols) (Gough and others, 2005). Discontinuous permafrost is found throughout the region and was typically observed at 15 to 50 centimeters (cm) below the surface at the soil sample sites (Gough and others, 2005). Soils in the study area typically had distinguishable A, B, and C horizons. The A and B horizons were usually less than 10 cm thick. The A horizon was typically dark brown with abundant root penetration, while the B horizon was lighter and more reddish than the A horizon and had moderate root volume. The C horizon was about 20 cm below the surface and consists of fine to coarse sand with blocks of angular bedrock and few roots (Gough and others, 2005).

The regional geology is described in detail in Day and others (2003) and condensed here as figure H1. Paleozoic gneisses are the predominant lithologies, although the Goodpaster batholith occupies much of the north to northeastern region of the Big Delta B-2 quadrangle study area. Gold mineralization, such as that found on the Pogo deposit, is associated with various phases of the Cretaceous plutonic rocks, which intrude the gneissic units (Smith and others, 1999; Day and others, 2003). Mineralization is also associated with dikes found in the eastern edge of the study area (Day and others, 2003).

Methods

Site selection, sampling, and analytical methods, as well as the complete analytical data for these samples, are given in detail in Gough and others (2005) and Wang and others (2006). Water and soil sites were selected on the basis of the regional geology and represent both mineralized and nonmineralized areas. Sites selected included (1) those that characterize the regional influence of the various lithologic units on the soil and water geochemistry and (2) downstream

sequences designed to characterize the localized influence of mineralized areas, changes in lithology, or cross-cutting structural features.

Results and Discussion

The elements Sb, As, Ba, Be, Cd, Cr, Cu, Pb, Hg, Ni, Se, Ag, Tl, and Zn are all those for which either Water Quality Criteria for Priority Toxic Pollutants and (or) Primary Drinking Water Standards are available (State of Alaska, 2003). Of these fourteen elements, Be, Cr, Se, Ag, and Tl were not detected in any of our samples, and Hg concentrations were not determined (Wang and others, 2006). The concentration ranges for Sb, As, Ba, Cd, Cu, Pb, Ni, and Zn and their relevant standards are given in table H1. Samples collected from one site exceeded the drinking water standard for As. The spatial distribution of As concentrations in water samples is shown in figure H2. Those samples with detectable As concentrations were typically found near mineralized areas. A similar pattern was found for Sb and, in general, detectable concentration of As and Sb were found only in samples adjacent to, or downstream from, mineralized areas (Wang and others, 2005).

Bed sediments near mineralized areas also showed elevated As concentrations relative to nonmineralized areas. In bed sediments, Au and As correlated well, and the highest values of both were located along Liese and Occidental Creeks (fig. H3). Ni, Cr, Fe, Mn, and Co concentrations in bed sediment were also correlated. The greatest concentrations of these elements were located along Sonora Creek and may reflect the presence of ultramafic rock units in the area (Wang and others, 2005).

Aqueous Major-Ion Chemistry

On a plot of total dissolved solids versus the ratio of Na to Na plus Ca ($\text{Na}/(\text{Na}+\text{Ca})$) in stream waters, the data points lie in the general region of rock-dominated systems as defined by Gibbs (1970) (fig. H4A), indicating that the composition of these samples is more rock dominated, as opposed to evaporation or precipitation dominated. The stream waters are classified primarily as Ca and Mg bicarbonate (Ca^{2+} and Mg^{2+} - HCO_3^-) to Ca and Mg sulfate (Ca^{2+} and Mg^{2+} - SO_4^{2-}) (fig. H4B). Waters draining the gneissic and intrusive lithologies of the study area can be differentiated on the basis of their major-ion chemistry (Wang and others, 2005). Stream waters draining gneissic units are more SO_4^{2-} dominated than those draining granitic units (fig. H5). Wang and others (2005) also found that the anionic composition of water in creeks draining the mineralized area was more SO_4^{2-} dominated. However, they concluded that the underlying paragneiss unit in this region could be contributing substantially to the SO_4^{2-} concentrations in these watersheds, and the increase in the SO_4^{2-} concentration

Table H1. Aqueous concentration ranges for selected regulated metals and corresponding State of Alaska Water Quality Criteria and Primary Drinking Water Standards.

[Abbreviations are as follows: mg/L, milligrams per liter; µg/L, micrograms per liter; mg/kg, milligrams per kilogram; –, not listed]

Element	Concentration range (µg/L)	Aquatic life criteria for fresh waters		Drinking water primary maximum contaminant level ¹ (µg/L)
		Acute (µg/L)	Chronic (µg/L)	
Sb	<0.1–0.7	–	–	6
As	<1–14	340	150	10
Ba	5.4–31.8	–	–	2,000
Cd	<0.02–0.04	2.13*	0.27*	5
Cu	<0.5–2	14*	9.33*	1,300*
Pb	<0.09–0.84	81.65*	3.18*	–
Ni	<0.45–3.3	469.16*	52.16*	–
Zn	<0.7–4.7	119.82	119.82	–

¹ Source: State of Alaska, Department of Environmental Conservation (2003).

*These aquatic life criteria (acute and chronic) are a function of the hardness of the water. Value given corresponds to a hardness of 100 mg/L calcium carbonate.

**Human health criteria for noncarcinogens, for consumption of water plus aquatic organisms.

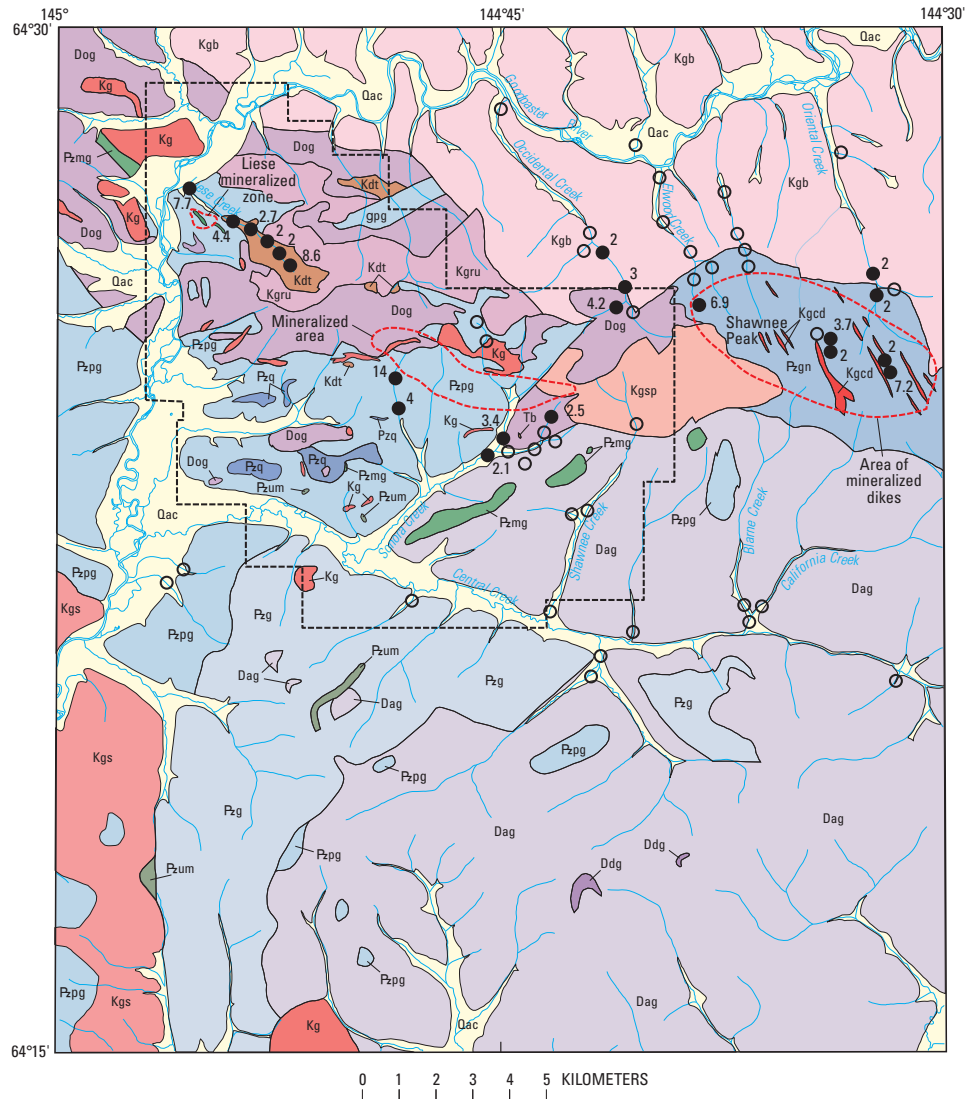
may reflect a complex batholith/paragneiss boundary rather than sulfide oxidation.

Arsenic and Antimony in Soil and Selected Vegetation

The primary arsenic- and antimony-containing minerals in the mineralized areas are pyrite, loellingite, arsenopyrite, and other sulfide minerals (Smith and others, 1999). In soils, arsenic and antimony may be present in either residual primary mineral phases or in secondary weathering products formed during soil formation. The arsenic in the A, B, and C soil horizons ranged from 3 to 410 milligrams per kilogram (mg/kg), 6.1 to 440 mg/kg, and 2 to 300 mg/kg, respectively, whereas antimony concentrations in these horizons ranged from 0.4 to 24 mg/kg, 0.6 to 25 mg/kg, and 0.2 to 16 mg/kg, respectively. The concentrations of arsenic and antimony among the soil horizons were highly correlated, and the concentrations of both typically increased in the order A < B < C horizon. Consequently, higher concentrations of arsenic and antimony in the A horizon were generally found in those soils with high concentrations in the B and C horizons (fig. H6). The greatest concentrations of both elements were generally found near mineralized areas (Wang and others, 2007). The arsenic and antimony concentrations in stream waters collected near the soil sites correlate well with the total arsenic and antimony concentrations in the soils from all horizons (Wang and others, 2007); however, significantly less of the total arsenic and antimony in the C horizon was extractable in water leaching experiments compared to that extracted from the A and B horizon samples. The greater extractability of the arsenic and antimony in the A and B

horizons indicates that a greater proportion in these horizons is present in more easily available forms. The lower extractability of the arsenic and antimony in the C horizon could arise if a greater proportion of the element is present in resistant primary mineral phases rather than on exchange surfaces (Wang and others, 2007).

The arsenic and antimony data for the willow samples are highly censored, with nearly half of the samples falling below the detection limit. Arsenic concentrations in willow ranged from less than 0.01 to 0.14 mg/kg (dry weight) for leaves and less than 0.01 to 0.16 mg/kg for twigs. The concentration range of arsenic in willows is consistent with arsenic concentrations of plants grown in uncontaminated soil (Kabata-Pendias and Pendias, 2001) and may indicate minimal plant uptake even in the mineralized regions. Antimony concentrations in both the willow leaves and twigs ranged from less than 0.003 to 0.23 mg/kg and less than 0.002 to 0.05 mg/kg, respectively. Arsenic and antimony concentrations in the leaves and twigs were correlated, but significantly more antimony is found in the leaves than in the twigs (Wang and others, 2007). Arsenic concentrations, however, did not differ between the twigs and leaves. Plant arsenic and antimony concentrations did not correlate with the A, B, and C soil horizon concentrations or the soil extractable concentrations. Lack of correlation between the plant concentrations and either the total or water-extractable soil concentrations also suggests the limited bioavailability of these elements within the system; however, the small number of data pairs coupled with the large amount of censored data made evaluation difficult.



EXPLANATION

Qac Alluvium and colluvium, undifferentiated (Quaternary)

Tb Basalt (Tertiary)

Igneous rocks (Cretaceous)

Kdt Diorite and tonalite

Ksp Rocks of the Shawnee Peak intrusion

Kgs Granite of Swede Peak

Kg Granite stock

Kgb Rocks of the Goodpastor batholith

Kgd Granitoid dike

Kgru Granitoid, undifferentiated

Metamorphic rocks (Devonian)

Dag Augen gneiss

Ddg Diorite gneiss

Dog Orthogneiss

Metamorphic rocks (Paleozoic)

Pzmg Mafic gneiss

Pzum Ultramafic gneiss

Pzq Quartzite

Pzpg Paragneiss

Pzg Biotite gneiss

Pzgn Biotite-sillimanite gneiss

--- Approximate boundary of mineralized area

----- Approximate boundary of Pogo property

Location of stream water sample and arsenic concentration

○ Arsenic in stream water less than 1 microgram per liter

●₂ Arsenic in stream water greater than 1 microgram per liter—Numbers indicate values in micrograms per liter. Exceeds Alaska State Drinking Water Standards

Location map



Figure H2. Concentration and distribution of arsenic in stream water plotted on a simplified regional geology map, Pogo deposit region, eastern Alaska.

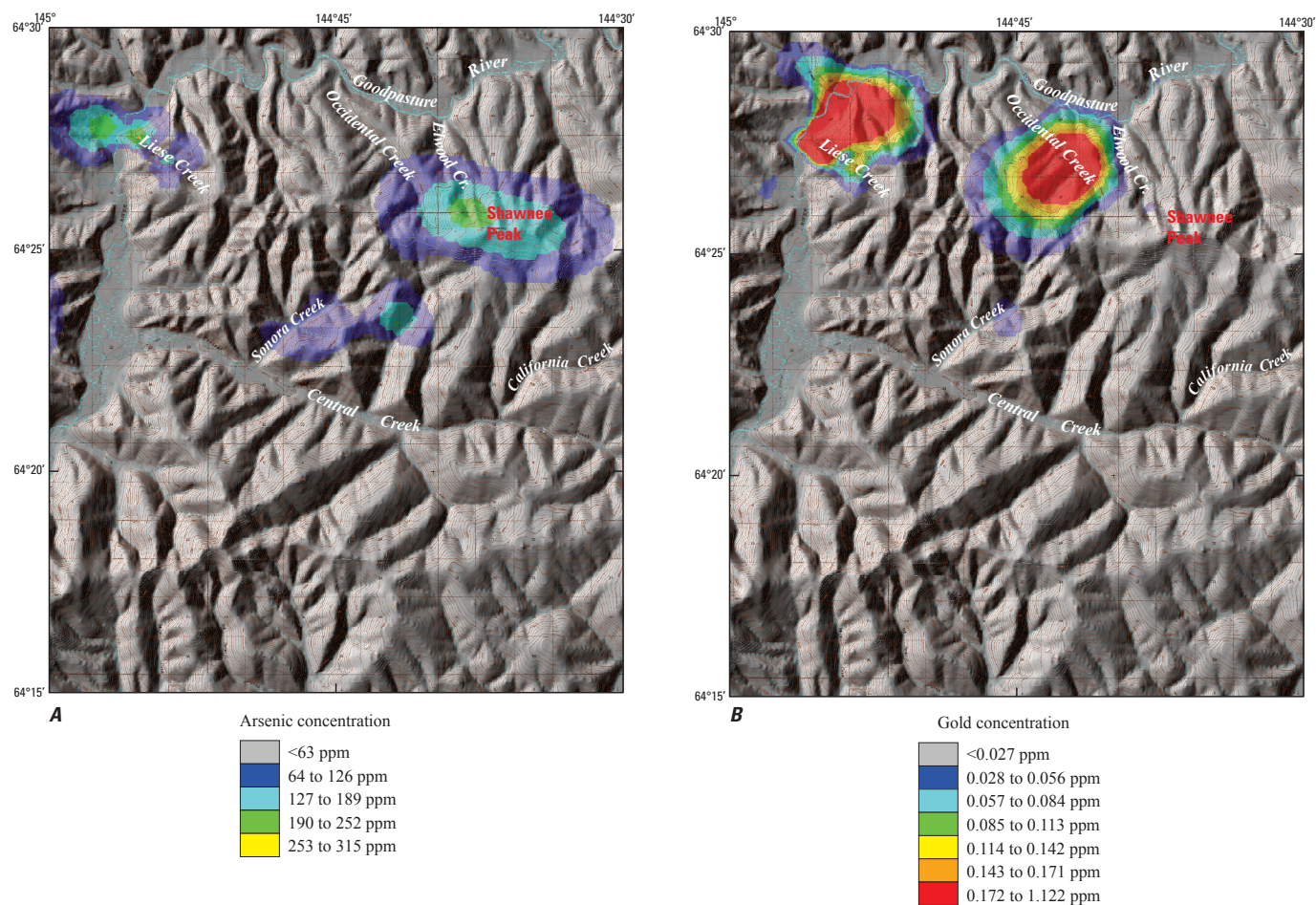


Figure H3. Shaded-relief maps showing the concentration and distribution of arsenic and gold in bed sediments, Pogo deposit region, eastern Alaska. *A*, Arsenic; *B*, Gold. ppm, parts per million.

Summary

In general, aqueous metal concentrations were below the Aquatic Life Criteria and Drinking Water Standards (State of Alaska, 2003); however, arsenic exceeded drinking water standards in one sample from a stream that drained a mineralized area. Both aqueous arsenic and antimony concentrations were greatest near mineralized areas, consistent with the oxidation of minerals, such as arsenopyrite, found in the region. The arsenic and antimony concentrations in stream waters correlated well with the total arsenic and antimony concentrations in the soils, but uptake by the vegetation examined appears minimal. Although the anionic composition of creeks draining the mineralized areas is also consistent with pyrite oxidation, the potential exists that the underlying paragneiss unit in this region is contributing substantially to the sulfate concentrations. Consequently, the presence of arsenic and (or) antimony in the water is the strongest indicator of a mineralizing influence in these waters. Bed sediments near mineralized areas also showed elevated arsenic concentrations relative to nonmineralized areas. Bed sediment arsenic concentrations were also highly correlated

with gold concentrations, whereas nickel, chromium, iron, magnesium, and cobalt appear to reflect the presence of ultramafic rocks within the watershed.

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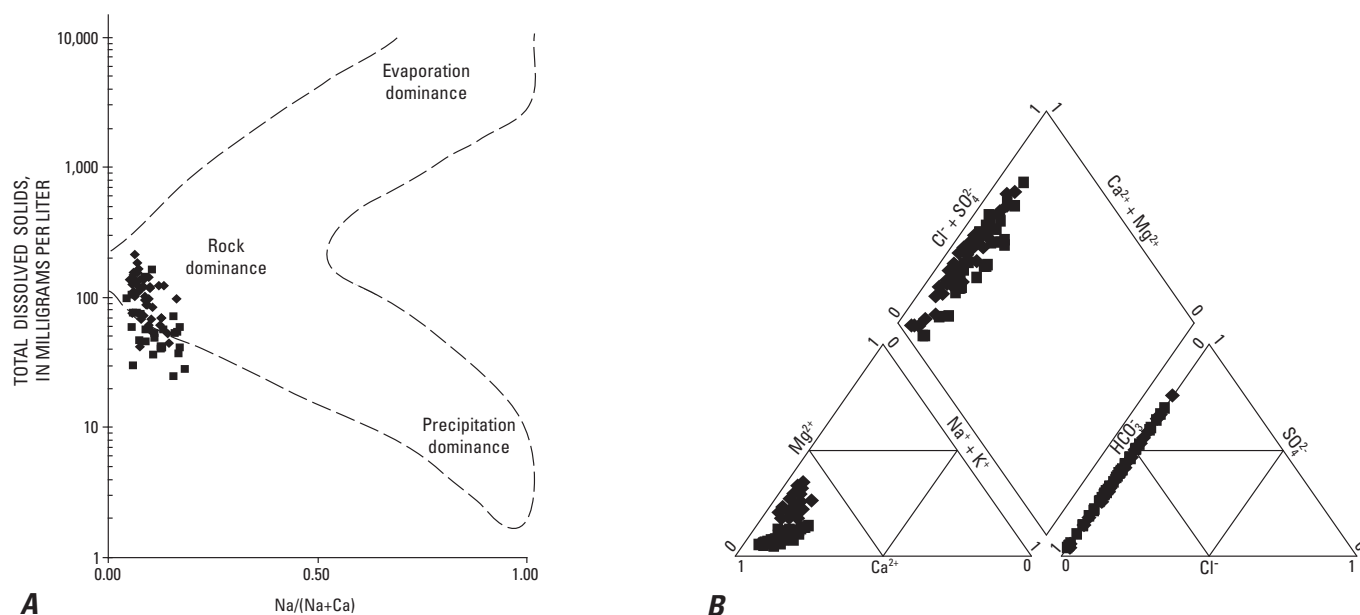


Figure H4. Graph and diagram showing the major-ion characteristics of the water. *A*, Graph showing total dissolved solids versus Na/(Na+Ca) ratio. “Boomerang” envelope approximated from Gibbs (1970). *B*, Trilinear diagram showing the range of major-ion composition. Diamonds and squares are samples collected in 1999 and 2001, respectively.

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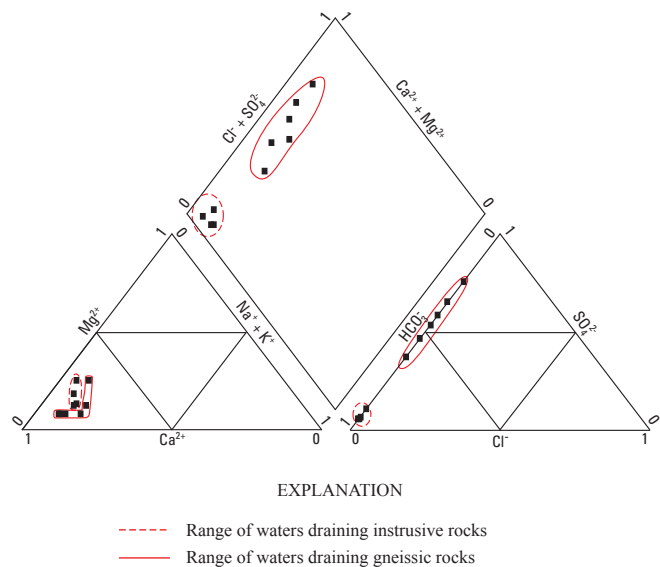
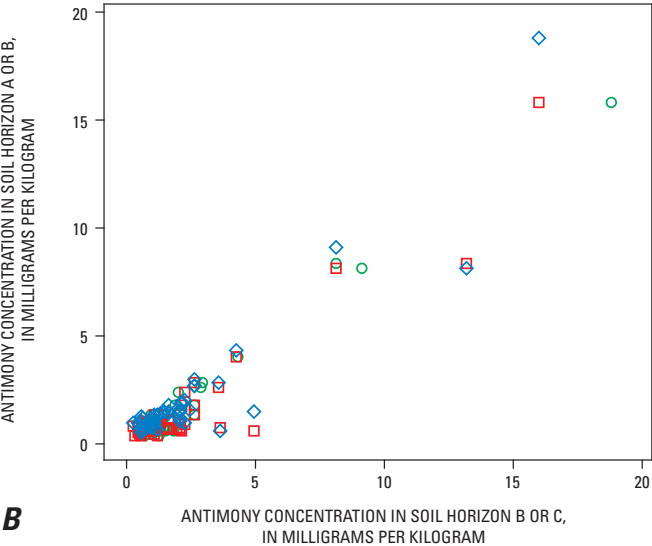
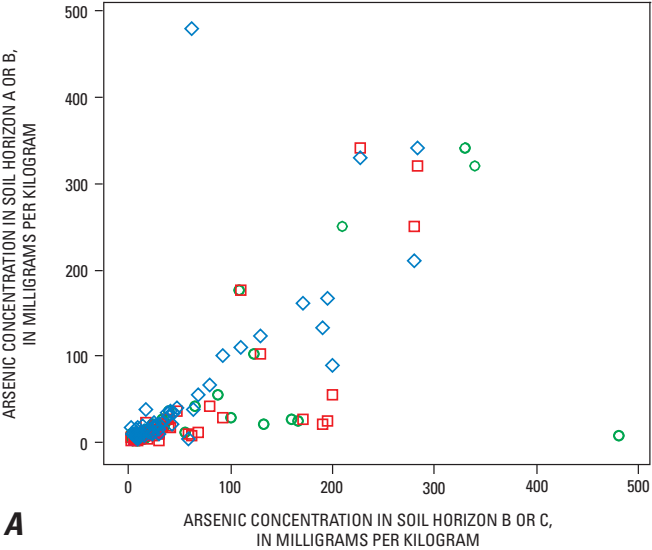


Figure H5. Trilinear diagram showing the compositional range of the major ions for waters draining the intrusive and gneissic rocks, Pogo deposit region, eastern Alaska.



EXPLANATION
[for parts A and B]

- Comparison between soil horizons A and B
- Comparison between soil horizons A and B
- ◇ Comparison between soil horizons A and B

Figure H6. Graphs showing arsenic and antimony concentrations of soil horizons, Pogo deposit region, eastern Alaska. A, Arsenic, B, Antimony.