

Anomalous gold, antimony, arsenic, and tungsten in ground water and alluvium around disseminated gold deposits along the Getchell Trend, Humboldt County, Nevada

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Abstract

Ground-water, alluvium, and bedrock samples were collected from drill holes near the Chimney Creek, Preble, Summer Camp, and Rabbit Creek disseminated gold deposits in northern Nevada to determine if Au and ore-related metals, such as As, Sb, and W, are being hydromorphically mobilized from buried mineralized rock, and, if they are, to determine whether the metal-enriched ground water is reacting with the alluvial material to produce a geochemical anomaly within the overburden.

Results of chemical analyses of drill-hole water samples show the presence of hydromorphic dispersion anomalies of Au, As, Sb, and W in the local ground-water systems associated with these deposits. Background concentrations for Au in the ground water up-gradient from the buried deposits was less than 1 nanogram per liter (ng/L), near the deposits the Au values ranged from 1 to 140 ng/L, and in drill holes penetrating mineralized rock, concentrations of Au in the ground water were as high as 4700 ng/L. Highest concentrations of Au were found in ground-water samples where the measured E_h and the distribution of arsenic species, arsenite [As(III)] and arsenate [As(V)], indicated oxidizing redox potentials. Similarly, As, Sb, and W concentrations in the ground water near the deposits were significantly enriched relative to concentrations in the ground water up-gradient from the deposits. In general, however, the highest concentrations of As, Sb, and W occurred in ground-water samples where the measured E_h and the distribution of arsenic species indicated reducing conditions. Arsenic concentrations ranged from 9 to 710 micrograms per liter ($\mu\text{g/L}$); Sb, from less than 0.1 to 250 $\mu\text{g/L}$; and W, from 1 to 260 $\mu\text{g/L}$.

In addition, analysis of sequential dissolution and extraction solutions of drill cuttings of alluvium and bedrock indicate geochemical anomalies of gold and ore-related metals in the overburden at depths corresponding to the location of the present-day water table. This relationship suggests that water-rock reactions around these buried deposits are active and that this information could be very useful in exploration programs for concealed disseminated gold deposits.

1. Introduction

The Preble, Pinson, Summer Camp, Getchell, Rabbit Creek, and Chimney Creek¹ disseminated gold deposits are located in Kelly Creek Valley, about 45 miles northeast of Winnemucca in Humboldt County, Nevada (Fig. 1). The gold deposits are hosted primarily in siliciclastic sediments, volcanics, and limestones of upper Cambrian and lower Ordovician age (Hotz and Willden, 1964; Kretschmer, 1984; Parratt et al., 1989) and the gold generally occurs as sub-micron size particles of native gold. Other minerals occurring with these Carlin-type gold deposits include orpiment (As_2S_3), realgar (AsS), and stibnite (Sb_2S_3).

Slowly moving ground water in contact with buried ore deposits may dissolve and transport trace elements that are associated with the deposits and thus form aqueous dispersion patterns (Fig. 2). The formation and geometry of the hydromorphic dispersion anomaly can be influenced by local hydrological, geological, and geochemical conditions. The detection of these dispersion patterns, by collecting and analyzing ground water, forms the basis of hydrogeochemical exploration (Boyle et al., 1971; Levinson, 1974; and Miller, 1979). The hydrogeochemical study in Kelly Creek Valley was undertaken to determine if the chemistry of ground water, collected from drill holes, would reveal the presence of the concealed gold deposits. If hydromorphic dispersion anomalies are present around these

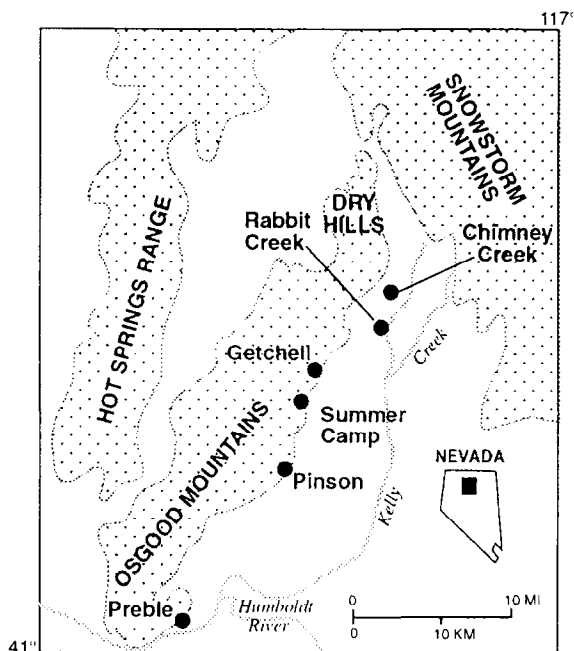


Fig. 1. Location of the Preble, Pinson, Summer Camp, Getchell, Rabbit Creek, and Chimney Creek disseminated gold deposits in northern Nevada.

¹ The Chimney Creek Mine and the Rabbit Creek Mine were combined in June 1993. The new mine is named the Santa Fe Pacific Gold Corp. Twin Creeks Mine.

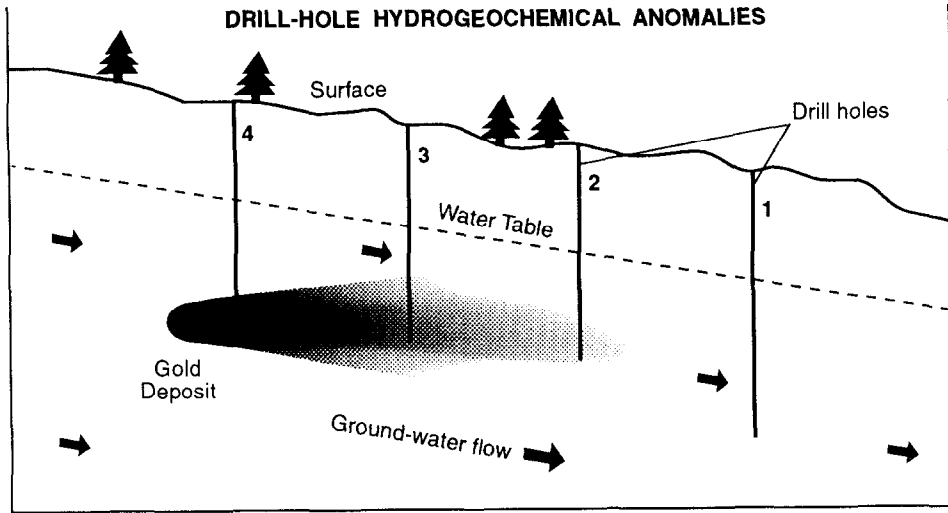


Fig. 2. Diagram illustrating a ideal hydromorphic dispersion anomaly of gold in the ground water, down-gradient from a concealed disseminated gold deposit. The dispersion anomaly for gold in the ground water is potentially a much larger drilling target than the gold deposit itself.

deposits, then hydrogeochemical techniques may be useful in discovering similar concealed disseminated gold deposits in Nevada and elsewhere.

Ground-water samples were collected in the vicinity of the known gold deposits during active drilling and from exploration drill holes that were several years old (Figs. 3, 4 and 5). The samples were analyzed to determine several constituents, including gold at the 1-ng/L level (note: 1 ng/L equals 1 part-per-trillion).

Gold and ore-associated elements that are mobilized from primary and secondary minerals by chemical reactions with the ground water may move in solution from buried deposits to

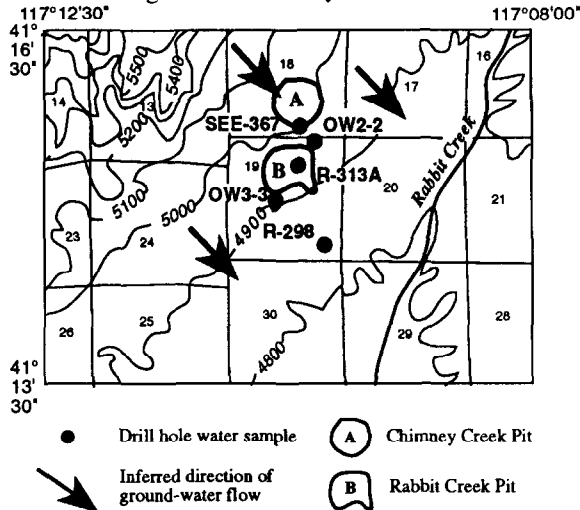


Fig. 3. Location of drill hole sites around the Chimney Creek and Rabbit Creek gold deposits (now called the Twin Creeks Gold Mine) where samples were collected for this study. Topographic contours are given in feet.

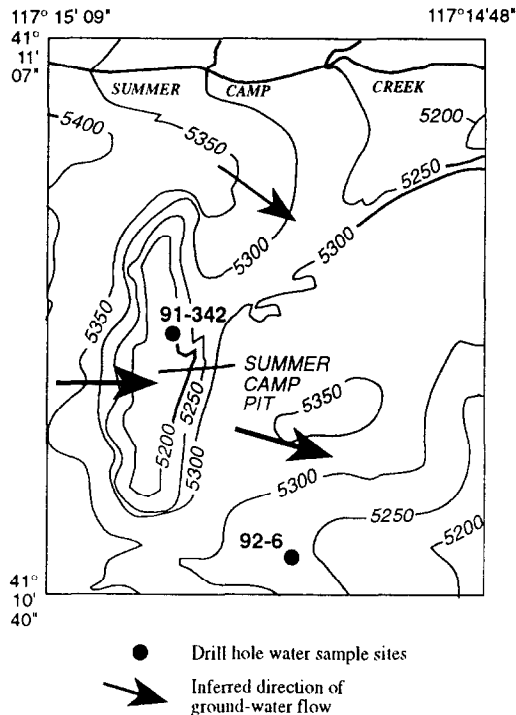


Fig. 4. Location of drill hole sites around the Summer Camp disseminated gold deposit where samples were collected for this study. Topographic contours are given in feet.

the near surface environment along hydrologic pathways, such as open pores, joints, bedding planes, fractures, and faults. Near the surface, the mobilized metals may precipitate or be removed from solution at reaction sites on clay, organic material, carbonates, manganese oxides, iron oxides, and secondary sulfides. These water–rock reactions involving adsorption, precipitation, and coprecipitation could produce geochemical anomalies as surface coatings on solid phase material located down-gradient from the buried deposit. In exploration geochemistry, it is often important to determine the distribution of pathfinder metals in the various chemical phases in order to obtain information on the origin and mode of occurrence of the ore-associated trace elements. The use of partial dissolution techniques in exploration has been discussed by Filipek and Theobald (1981), Chao (1984), Crone et al. (1984), Batley (1989), and Hall et al. (1993).

The sequential dissolution procedure used in this study was designed to determine if Au and ore-associated metals are partitioned into one or more chemical phases in the alluvial cover above and around the buried disseminated gold deposits. These data may provide important information on water–rock reactions taking place between alluvial material and ground water in contact with the buried deposits.

Reverse-circulation rotary-drill cuttings of alluvium and bedrock were obtained from several of the drill holes where water samples had been collected (Figs. 3, 4 and 5). The samples were subjected to a 5-step sequential dissolution and extraction procedure designed to dissolve and separate chemical phases of the alluvial and bedrock material. Each solution

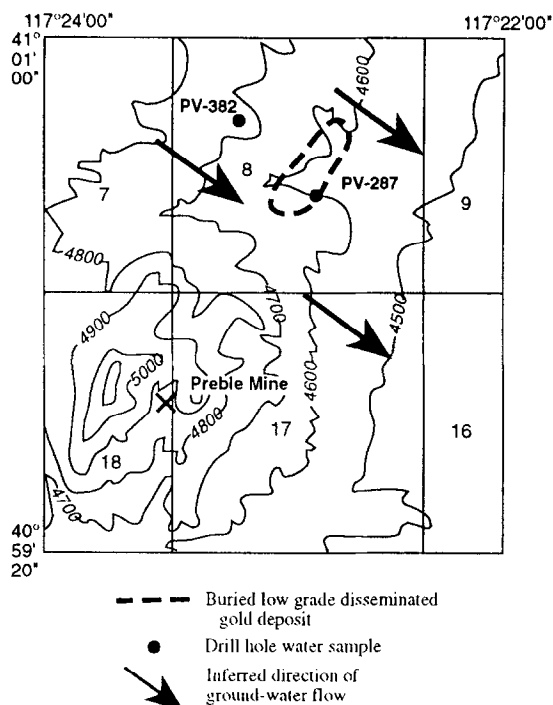


Fig. 5. Location of drill hole sites near a buried disseminated gold deposit, 3 km northeast of the Preble gold deposit, where samples were collected for this study. Topographic contours are given in feet.

was analyzed to determine 18 elements using inductively coupled plasma-atomic emission spectroscopy (ICP-AES).

2. Sample collection, preparation, and analytical procedures

2.1. Ground water

Ground-water samples were collected during active drilling from reverse-circulation rotary drill rigs. The samples were taken at 60- to 100-ft intervals during drill-pipe changes, immediately after water in the drill hole had been purged. No drilling mud was used in any of the drill holes sampled, and little, if any, injection water was added. The water samples from the old drill holes were collected at and below the water table using a custom-built double-check valve bailer with a maximum volume of 1.25 L. The open top point source bailer is constructed of polyvinyl chloride and has an outside diameter of 1.66 in and a 4 ft transparent body section. The bailer is manually lowered into the drill holes on nylon cord to sampling depths as great as 700 ft below the ground surface. The check-valve system of the bailer allows water to flow through the bailer as it is lowered down the drill hole. When the desired sampling depth is reached the downward motion of the bailer is stopped, the check valves close, and the water at that depth (± 10 ft) is trapped inside the bailer. A ball check valve at the top of the bailer allows water to be sampled and retrieved from any

desired depth below the water table without being mixed with water from above as the bailer is withdrawn from the drill hole.

A 50-mL water sample from each site was filtered in the field through a 0.45-micron membrane filter and acidified to a pH of about 2 with five drops of concentrated nitric acid. Two water samples with volumes of about 200 mL and 1000 mL were also collected at each site and filtered through a 0.45-micron filter. For samples selected for the determination of the arsenic species, arsenite [As(III)] and arsenate [As(V)], a 10-mL aliquot of water was filtered through a 0.45-micron filter and preserved with one drop of concentrated hydrochloric acid. All the samples were stored in acid-rinsed polyethylene bottles. Temperature, specific conductance, and pH were also measured at each site. The specific conductance and pH determinations were made using pocket sized meters with automatic temperature compensation. E_h was measured in the field for water samples collected from old drill holes by means of a combination platinum electrode.

Gold was determined in the 1000-mL water samples by graphite-furnace atomic-absorption spectrometry after acidification and preconcentration using anion-exchange resins (McHugh, 1986). Concentrations of the arsenic species, As(III) and As(V), were determined by anion-exchange graphite-furnace atomic-absorption spectrometry (Ficklin, 1983). The concentrations of these two species of arsenic commonly provide an approximation of the relative oxidation–reduction conditions (redox potential) present at the depth of sample collection. Where most of the arsenic occurs as As(III), the redox potential of the ground water is relatively more reducing than that of ground water where the arsenic occurs predominately as As(V) and visa versa. Chloride and SO_4 were determined in the 200 mL unacidified sample by ion chromatography (Fishman and Pyen, 1979). Iron, Mn, and Na were determined by flame atomic absorption spectrophotometry (Perkin-Elmer Corp., 1976).

Antimony, As, Co, and W are determined directly on the filtered samples which were acidified with nitric acid, using inductively coupled plasma mass spectrometry (ICP-MS). Two (2.0) micrograms of indium are added to each 10 mL of sample, blank, and standard solution as an internal standard to correct for sample matrix variability and instrumental fluctuations. All samples and standards are background-corrected by subtracting the average background counts observed at mass 230. All standards and samples are blank-corrected using acidified deionized water as the blank solution. Calibration standards are prepared to contain 100 $\mu\text{g/L}$ each of the elements of interest. Two-point calibration is used because the calibration curves for all elements are linear over six orders of magnitude in concentration. If chloride is present in the sample, interference can occur for the As measurement. The two isotopes of chlorine, ^{35}Cl and ^{37}Cl , form polyatomic ions with the ^{40}Ar of the plasma to give $^{75}\text{ArCl}^+$ and $^{77}\text{ArCl}^+$. The correction is made by multiplying the abundance ratio of the Cl isotopes, 3.13, times the ion count measured at mass 77, and the result is subtracted from the ion count measured at mass 75. Any remaining counts are assigned to As in the sample. In this study a Sciex Elan model 250 ICP-MS system was used with instrumental parameters set to give maximum sensitivity over the entire mass range.

2.2. Drill cuttings of alluvium and bedrock

Reverse-circulation rotary-drill cuttings of alluvium and bedrock were obtained from several of the drill holes where water samples had been collected. Five- or 10-foot com-

posites of the drill cuttings were sampled at 20-ft intervals. Samples of alluvium collected from drill holes R-313A and R-298 at the Rabbit Creek Mine (Fig. 3) were sieved to –250 mesh (0.06 mm), and these splits were used for the analysis. Bedrock samples were crushed in a jaw crusher and then ground to approximately 200 mesh (0.08mm) in a vertical pulverizer equipped with ceramic plates. The rock samples were subjected to a sequential dissolution and extraction procedure designed to dissolve and separate chemical phases of the alluvial and bedrock material. The sequential extraction sequence was based on a procedure described by Chao (1984) and was specifically formulated to differentiate elements present in hydromorphically transported phases from those elements occurring primarily in clastic or resistant mineral. This 5-step sequential extraction scheme was designed to dissolve and separate operationally defined chemical phases of the samples in the following order: (1) carbonates and exchangeable metals; (2) Mn-oxides and amorphous Fe-oxides; (3) crystalline Fe-oxides; (4) sulfides and organics; and (5) the residue (“silicate fraction”).

In step 1 (carbonates and exchangeable metals), 25 mL of 1 M acetic acid were added to centrifuge tubes containing 1.0 g of sample and 0.5 g of SiO₂. The tubes were capped and shaken on a horizontal shaker at room temperature for 2 hours. The samples were then centrifuged and decanted, with the leachate saved for analysis.

In step 2 (Mn-oxides and amorphous Fe-oxides), 25 mL of 0.25 M hydroxylamine hydrochloride in 0.25 M hydrochloric acid (HCl) were added to the residual material from step 1 and heated in a water bath at 50°C for 30 minutes. The samples were then centrifuged and decanted, with the leachate saved for analysis.

In step 3 (crystalline Fe-oxides), 25 mL of 4 M HCl were added to the residual material from step 2 and heated in a water bath at 95°C for 30 minutes. The samples were centrifuged and decanted, with the leachate saved for analysis.

In step 4 (sulfides and organics), 2 g of potassium chlorate and 10 mL of concentrated HCl were added to the residual material from step 3. The samples were left to stand at room temperature for 45 minutes and then diluted with 15 mL of water. The samples were centrifuged and decanted, with the leachate saved for analysis.

In step 5 (residue or “silicate fraction”), 10 mL of concentrated nitric acid were added to 50-mL teflon beakers containing the residual material from step 4 and the resultant solutions were heated on a hot plate at 110°C for 10 minutes. Ten milliliters of perchloric acid and 10 mL of 48% hydrofluoric acid were added, and the sample solutions were heated on a hot plate at 220°C until a moist bead was obtained. Twenty-five milliliters of 4 M HCl were added, and the samples were heated at 100°C for 30 minutes. The solutions were transferred to test tubes, centrifuged, and decanted, with the liquid saved for analysis.

A separate total digestion was performed on the samples with a fresh 0.5 g sample split using the same procedure as in step 5 in order to compare the “total” metal concentrations to the sum of the sequential dissolutions of steps 1–5. Solutions were analyzed by induction coupled plasma-atomic emission spectrometry (ICP-AES) using operating parameters described by Motooka and Sutley (1982). For the samples analyzed in this study, the sum of the metal concentrations in the five extraction fractions generally was within ±15 percent of the total metal concentrations as determined by the separate total digestion. In the following discussions on metal speciations and mineral phases, phrases such as “occurs in”, “chemical host”, and “chemical phase of residence” are used. The sense of these

Table 1
Analytical results for water samples collected from drill holes near disseminated gold deposits along the Getchell Trend, Humboldt County, Nevada (<, not detected at the limit of determination shown; Spec. cond., specific conductance in $\mu\text{S}/\text{cm}$; -, no data)

| Sample number | Water sample depth (ft) | pH | E_h , mV | Au, ng/L | As(III), $\mu\text{g}/\text{L}$ | As(V), $\mu\text{g}/\text{L}$ | As, $\mu\text{g}/\text{L}$ | Sb, $\mu\text{g}/\text{L}$ | W, $\mu\text{g}/\text{L}$ | Fe, mg/L | Mn, mg/L | Co, $\mu\text{g}/\text{L}$ | Na, mg/L | SO ₄ , mg/L | Cl, mg/L | Spec. cond. | Temp., °C |
|--------------------------------------|-------------------------|-----|------------|----------|---------------------------------|-------------------------------|----------------------------|----------------------------|---------------------------|----------|----------|----------------------------|----------|------------------------|----------|-------------|-----------|
| Drill holes near Rabbit Creek | | | | | | | | | | | | | | | | | |
| OW2-2-A | 360 | 6.7 | -122 | 8 | 470 | 7 | 540 | 0.7 | 120 | 0.80 | 2.30 | 1.7 | 29 | 39 | 7 | 440 | 18.4 |
| OW2-2-B | 400 | 6.9 | -107 | 14 | 350 | 1 | 490 | 0.8 | 70 | 0.92 | 1.40 | 1.2 | 28 | 32 | 7 | 430 | 18.4 |
| OW2-2-C | 500 | 6.9 | -77 | 17 | 220 | 17 | 430 | 2.6 | 88 | 0.83 | 1.30 | 1.7 | 29 | 38 | 8 | 430 | 18.8 |
| OW2-2-D | 546 | 6.9 | -71 | 23 | 490 | 5 | 450 | 1.2 | 74 | 1.00 | 1.60 | 1.5 | 28 | 40 | 7 | 430 | 18.6 |
| OW3-3-A | 270 | 7.8 | 183 | 1 | <1 | 25 | 20 | 0.5 | 2 | 0.01 | <0.1 | 0.5 | 39 | 37 | 17 | 440 | 18.7 |
| OW3-3-B | 400 | 7.8 | 184 | 3 | <1 | 22 | 20 | 0.6 | 2 | 0.02 | <0.1 | 0.4 | 40 | 38 | 18 | 470 | 18.3 |
| OW3-3-C | 560 | 7.9 | 188 | 23 | <1 | 24 | 31 | 0.6 | 2 | 0.02 | 0.01 | 0.4 | 41 | 34 | 15 | 490 | 18.7 |
| SEE367-A | 390 | 7.3 | 160 | 1 | <2 | 660 | 600 | 110.0 | 130 | 0.01 | 0.11 | 0.7 | 22 | 59 | 9 | 450 | 17.8 |
| SEE367-B | 480 | 7.0 | 150 | 1 | 480 | 175 | 650 | 130.0 | 140 | 0.12 | 0.11 | 0.7 | 21 | 60 | 8 | 450 | 15.0 |
| SEE367-C | 560 | 7.3 | -10 | 2 | 750 | 50 | 710 | 140.0 | 140 | 0.21 | 0.07 | 0.3 | 22 | 60 | 7 | 450 | 17.2 |
| SEE367-D | 660 | 7.1 | 6 | 6 | 758 | 96 | 660 | 120.0 | 140 | 0.16 | 0.10 | 0.5 | 21 | 68 | 7 | 450 | 16.1 |
| SEE367-E | 720 | 7.3 | -6 | 11 | 800 | 40 | 680 | 140.0 | 140 | 0.21 | 0.08 | 0.4 | 22 | 61 | 7 | 450 | 16.7 |
| R298-A | 170 | 7.7 | 245 | 11 | <1 | 25 | 24 | 0.7 | 3 | 0.02 | <0.1 | 0.3 | 23 | 15 | 13 | 330 | 16.2 |
| R298-B | 500 | 7.6 | 248 | 26 | <1 | 25 | 27 | 0.9 | 3 | 0.01 | <0.1 | 0.3 | 23 | 20 | 17 | 360 | 16.4 |
| Summer Camp drill holes | | | | | | | | | | | | | | | | | |
| 91-342D-A | 80 | 8.0 | - | 4700 | <5 | 24 | 23 | 77.0 | 38 | <0.01 | 0.11 | 15.0 | 35 | 68 | 19 | 520 | 13.9 |
| 91-342D-B | 120 | 7.8 | - | 1100 | 10 | 31 | 40 | 65.0 | 22 | <0.01 | 0.07 | 6.4 | 30 | 41 | 19 | 420 | 15.7 |
| 91-342D-C | 160 | 7.9 | - | 640 | 9 | 52 | 68 | 180.0 | 23 | <0.01 | 0.06 | 3.9 | 30 | 41 | 19 | 430 | 15.6 |
| 91-342D-D | 200 | 8.0 | - | 370 | 10 | 25 | 44 | 250.0 | 24 | <0.01 | 0.08 | 2.8 | 28 | 32 | 17 | 420 | 16.4 |
| 92-6-A | 220 | 7.9 | - | - | - | - | 11 | 26.0 | 25 | <0.01 | 0.07 | 1.1 | 26 | 47 | 13 | 420 | - |
| 92-6-B | 280 | 8.0 | - | 10 | - | - | 55 | 110.0 | 100 | 0.01 | 0.10 | 1.5 | 23 | 43 | 15 | 390 | - |
| 92-6-C | 340 | 8.0 | - | 12 | - | - | 33 | 18.0 | 210 | 0.07 | 0.11 | 1.2 | 24 | 42 | 15 | 390 | - |
| 92-6-D | 400 | 7.8 | - | 100 | - | - | 24 | 17.0 | 140 | 0.15 | 0.15 | 1.1 | 25 | - | - | 390 | - |
| 92-6-E | 460 | 7.8 | - | 140 | - | - | 33 | 38.0 | 260 | 0.11 | 0.15 | 1.4 | 23 | 50 | 15 | 400 | - |
| Drill holes near Preble | | | | | | | | | | | | | | | | | |
| PV-287-A | 130 | 7.2 | -052 | <1 | 114 | <2 | 130 | 17.0 | 62 | 0.59 | 0.07 | 4.4 | 120 | 75 | 10 | 900 | 30.7 |
| PV-287-B | 200 | 7.5 | -015 | 1 | 95 | <2 | 77 | 15.0 | 61 | 0.02 | 0.06 | 4.9 | 120 | 77 | 9 | 910 | 30.4 |
| PV-287-C | 300 | 7.2 | -042 | 1 | 42 | <2 | 83 | 21.0 | 62 | 0.78 | 0.06 | 3.2 | 120 | 71 | 9 | 910 | 31.9 |
| PV-287-D | 400 | 7.5 | -049 | 1 | 20 | <2 | 49 | 24.0 | 63 | 0.03 | 0.06 | 1.6 | 120 | 63 | 9 | 890 | 32.1 |
| PV-287-E | 475 | 7.2 | -063 | <1 | 62 | <2 | 87 | 13.0 | 63 | 0.38 | 0.06 | 2.9 | 120 | 78 | 8 | 900 | 31.8 |
| PV-382-A | 210 | 8.1 | -050 | <1 | 9 | <2 | 10 | 0.1 | 2 | 0.02 | 0.02 | 0.1 | 94 | 55 | 32 | 630 | 17.4 |
| PV-382-B | 350 | 8.1 | -050 | 1 | 7 | <2 | 9 | 0.1 | 1 | <0.01 | 0.02 | 0.1 | 94 | 54 | 32 | 620 | 17.4 |

expressions is that the metal associations as determined by the sequential dissolution and extraction procedures such as those used in this study are “operationally defined”, “reagent and sample dependent”, and are not necessarily 100 percent selective (Chao, 1984; Hall et al., 1993). Alluvium samples from drill hole R-313A were subjected to a 4 N HCl digestion, described in step 3 above, and analyzed for Au using a graphite-furnace atomic-absorption spectrophotometric technique (McHugh, 1986). The resultant residues from the digestions were analyzed for Au by a graphite-furnace atomic-absorption method described by Meier (1980).

3. Results and discussion

Profiles of four drill holes showing the distribution of selected constituents in ground-water samples are presented in Figs. 6–9. Near the water table, at sample site SEE-367-A, the measured E_h and the high As(V) concentrations indicate oxidizing conditions (Fig. 6). However, with depth the ground water becomes more reducing. At a depth of 560 ft in drill hole SEE-367, the E_h value of the ground water is negative and the As(III) concentration is high relative to the As(V) concentration. This redox change in the ground water approximately coincides with the change in redox character of the bedrock (Fig. 6) and demonstrates the potential use of arsenic species as indicators of relative redox conditions in ground water. Iron concentrations increase from 0.01 mg/L for ground water near the water table at sample site SEE-367-A to 0.21 mg/L for ground water at a depth of 720 ft. The increase in dissolved Fe with depth correlates fairly well with the decrease in redox potential as indicated by the relative concentrations of the arsenic species. The concentration of dissolved Au varies from 1 ng/L at a depth of 390 ft to a high of 11 ng/L at 720 ft. The higher concentration of Au in the ground water at depth may be attributed to an increase in mineralization with depth. Similar correlations of dissolved arsenic species and E_h are also observed in water samples collected from drill holes OW2-2 and OW3-3 located near the Chimney Creek and Rabbit Creek disseminated gold deposits (Fig. 3). In drill hole

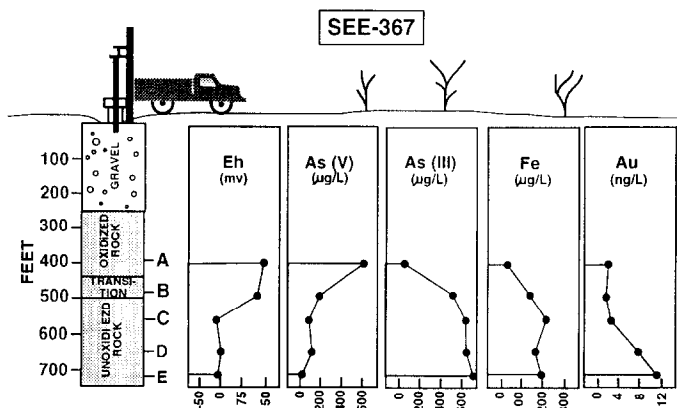


Fig. 6. Profile of drill hole SEE-367 showing the distribution of E_h , As(V), As(III), Fe, and Au in water samples collected at and below the water table. Note the change in water chemistry (E_h and arsenic species concentrations) at the bedrock redox boundary or transition zone.

OW2-2, the measured E_h is negative and the As occurs primarily as As(III) (Table 1). In drill hole OW3-3, the measured E_h is positive and the As occurs as As(V).

In drill hole R-298, the maximum Au and As concentrations in ground water in the alluvium above oxidized bedrock are 26 ng/L and 27 $\mu\text{g/L}$ respectively (Fig. 7). The E_h and arsenic species concentrations (Table 1) indicate oxidizing conditions in this drill hole, at least to the depth sampled. The ground-water anomalies here may be attributable to the hydromorphic dispersion of Au and As down-gradient from the mineralized bedrock at the Rabbit Creek deposit.

Gold concentrations in the water from drill hole 91-342, located over the Summer Camp disseminated gold deposit (Fig. 4), range from 4700 ng/L at a depth of 80 ft to 370 ng/L at a depth of 200 ft (Fig. 8). Concentrations of the arsenic species indicate oxidizing ground-water conditions at a depth of 80 ft where all of the measured As is present as As(V). However, below this depth, As(III) concentrations persist which indicate a relatively lower redox ground-water environment. This is similar to the ground-water conditions in drill hole SEE-367 with a redox change in the ground water approximately coinciding with a change in the redox character of the bedrock (Fig. 6). In the water from drill hole 91-342, a positive correlation of Au and Co with oxidized bedrock and a positive correlation As and Sb with unoxidized bedrock is shown (Fig. 8). The concentrations of Au and Co are highest in water sample 91-342-A, where the arsenic species indicate moderate oxidizing ground-water conditions. However, the As and Sb concentrations are highest in samples 91-342-C and 91-342-D, at depths where ground-water conditions are relatively reducing, as indicated by the As(III) concentrations. The ground water here is alkaline with a narrow pH range from 7.8 to 8.0. These relationships suggest a higher mobility for Au and Co under oxidizing alkaline ground-water conditions and a higher mobility for As and Sb under reducing alkaline ground-water conditions. These results are consistent with other studies showing mobilization of Au in neutral to alkaline waters under oxidizing conditions (Pitul'ko, 1976; Webster, 1986; Fedoseyeva and Strel'tsova, 1987; Vlassopoulos and Wood, 1990). Also, the increased solubilities of As and Sb in alkaline and relatively reducing ground water at

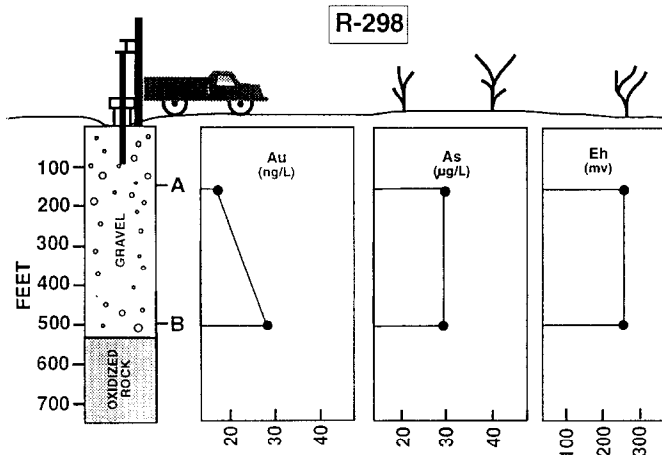


Fig. 7. Profile of drill hole R-298 showing the distribution of Au, As, and E_h in water samples collected at and below the water table. Note the anomalous concentrations of Au ($> 1 \text{ ng/L}$) and As ($> 5 \mu\text{g/L}$) in ground-water samples collected above the alluvium–bedrock contact.

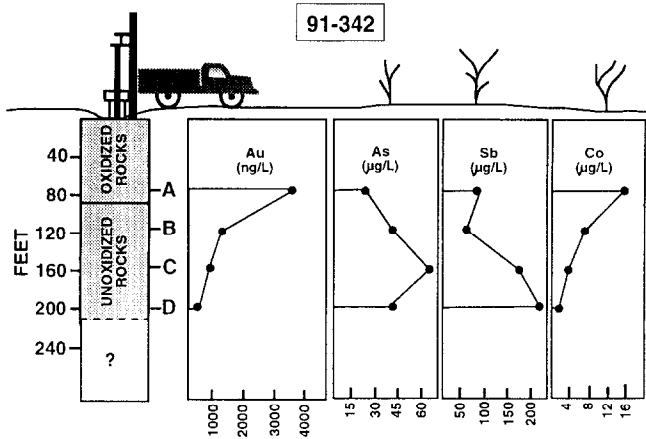


Fig. 8. Profile of drill hole 91-342 showing the distribution of Au, As, Sb, and Co in water samples collected at and below the water table. Note the positive correlation of Au and Co with oxidized bedrock and the positive correlation of As and Sb with unoxidized bedrock.

Summer Camp is similar to relationships reported elsewhere (Shvartsev et al., 1974; Welch et al., 1988; Masscheleyn et al., 1991). Data for water samples collected from drill hole 92-6, located down-gradient from the Summer Camp deposit (Fig. 4), indicates hydromorphic anomalies for Au, As, Sb, and W (Table 1). E_h and arsenic species determinations were not made on samples from drill hole 92-6 because the samples were not preserved immediately after collection. Consequently, the redox character of the ground water at this site cannot be established and redox correlations with dissolved constituents cannot be made. However, the ground water here is also alkaline with a narrow pH range from 7.8 to 8.0.

Fig. 9 shows the relationship of E_h , As(III), Sb, and W in ground-water samples collected from drill hole PV-287, located over an unnamed buried low grade disseminated gold

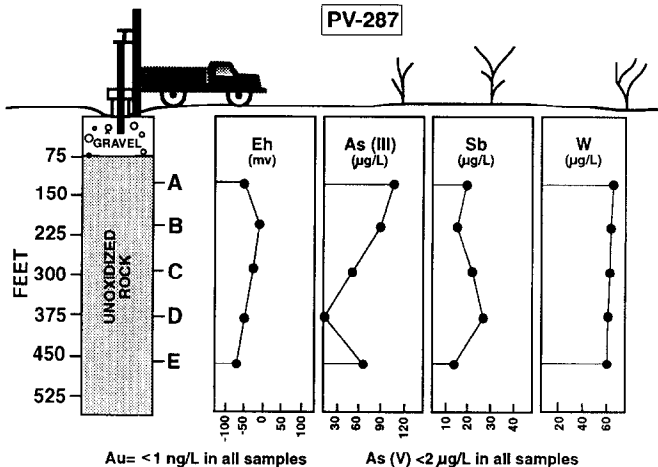
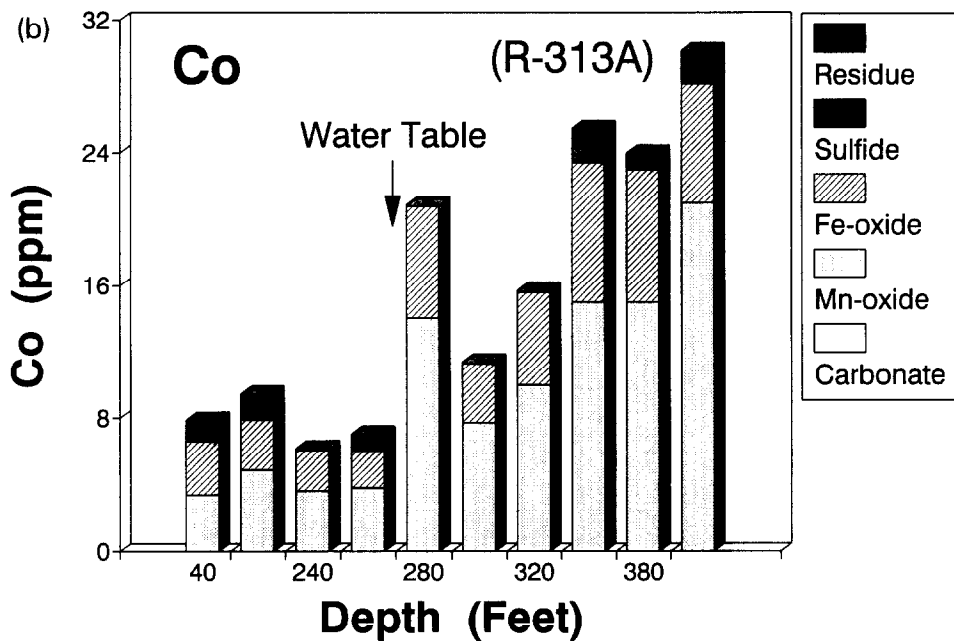
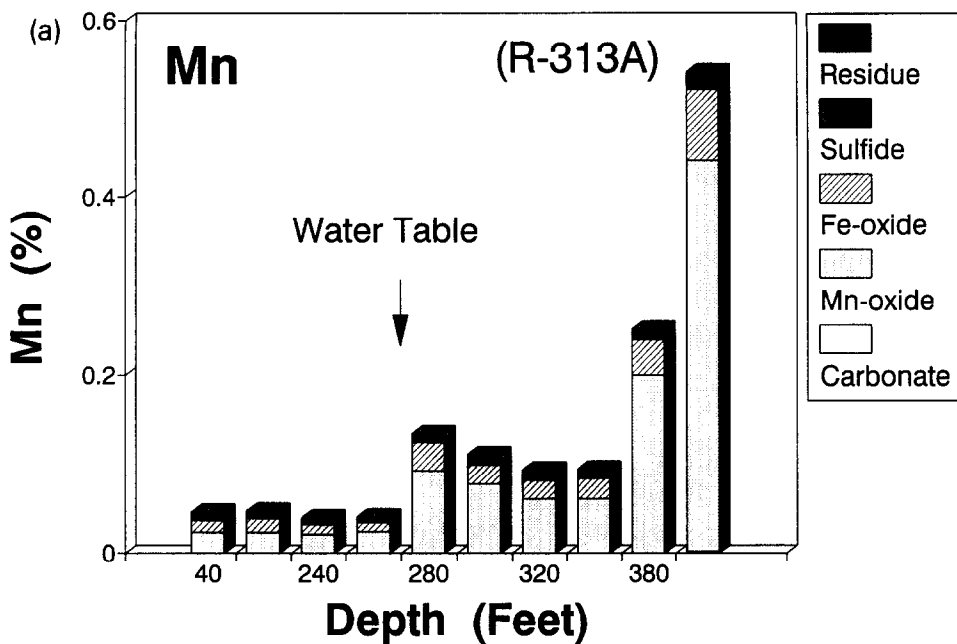


Fig. 9. Profile of drill hole PV-287 showing the distribution of E_h , As(III), Sb, and W in water samples collected at and below the water table. Note the low redox potential (negative E_h values and high concentrations of As(III)) of the ground water in contact with unoxidized bedrock.



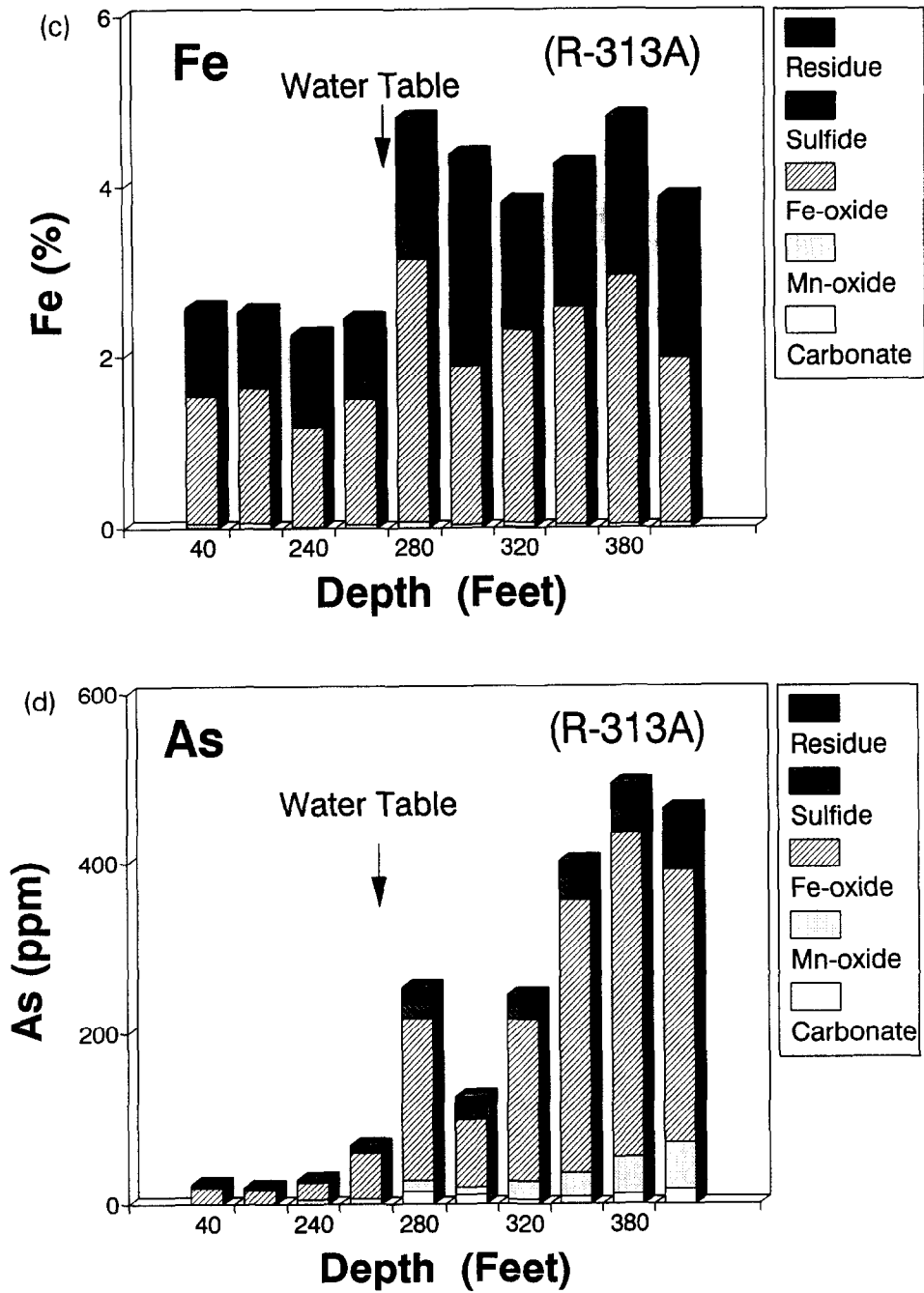


Fig. 10 (See p. 364 for caption.)

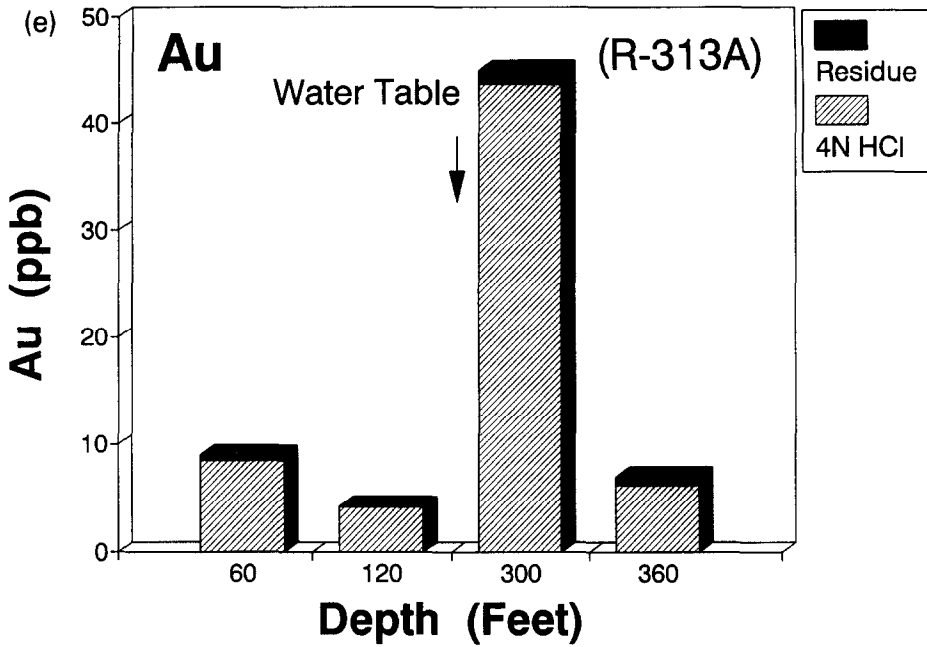
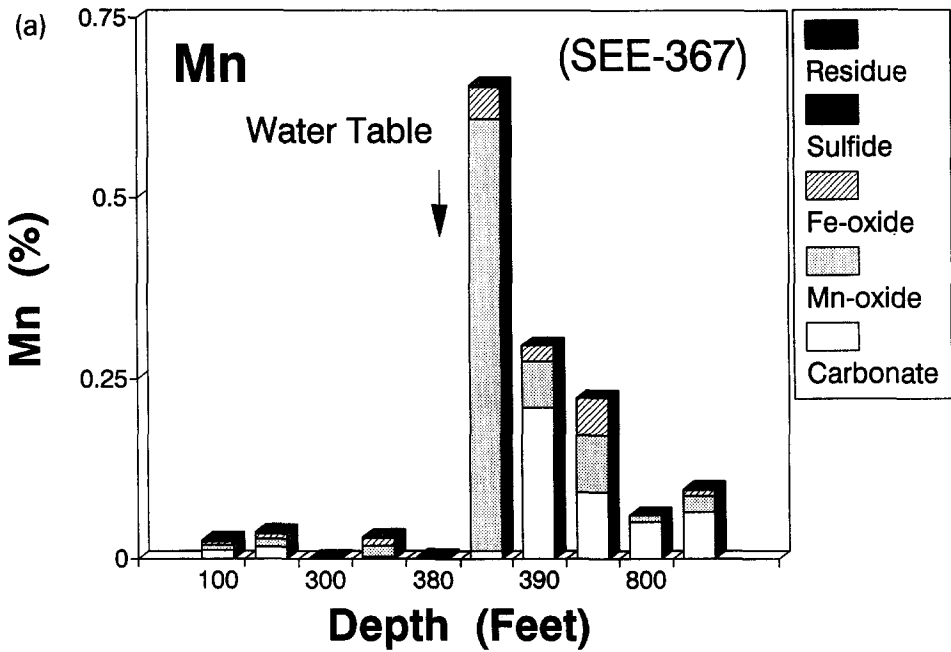


Fig. 10. Distribution of Mn (A), Co (B), Fe (C), As (D), and Au (E) in alluvial samples collected above the Rabbit Creek disseminated gold deposit from drill hole R-313A.



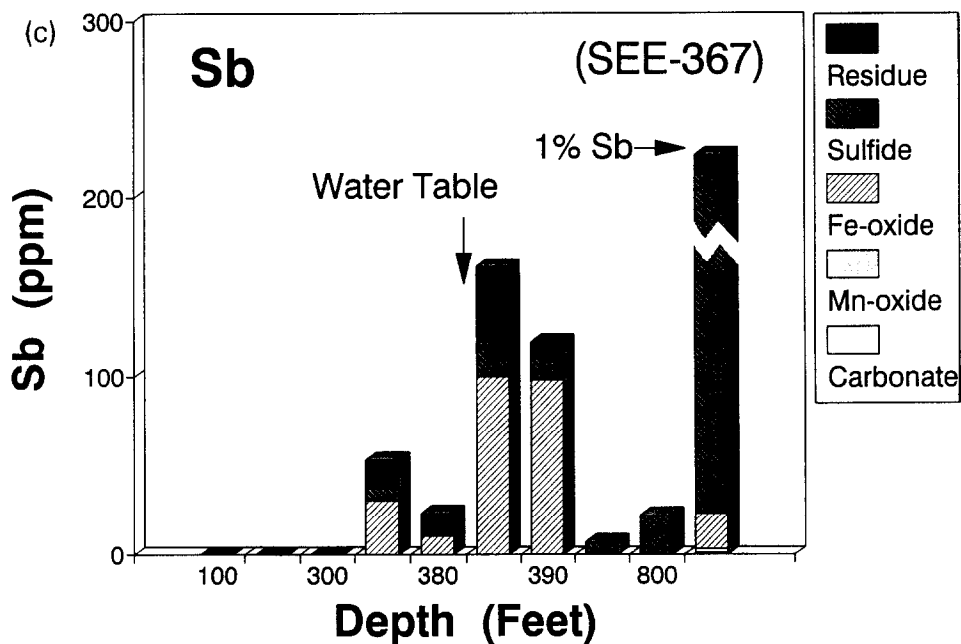
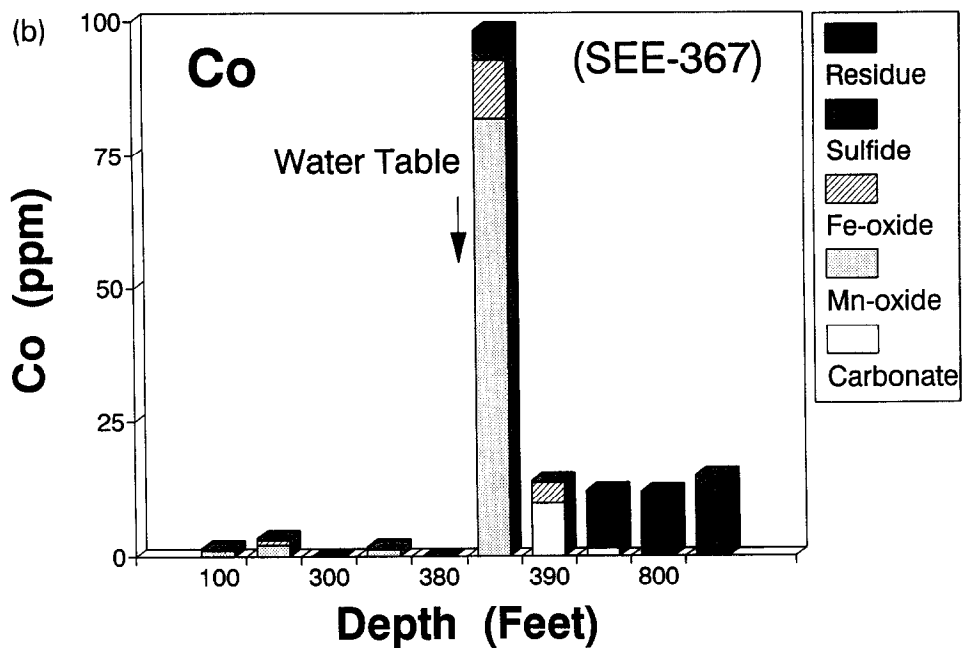


Fig. 11. Distribution of Mn (A), Co (B), and Sb (C) in bedrock samples collected from drill hole SEE-367, which is located between the Chimney Creek and Rabbit Creek disseminated gold deposits.

deposit northeast of the Preble gold mine (Fig. 1). The negative E_h values, the high concentrations of As(III), and the lack of detectable As(V) (Table 1) indicate reducing ground-water conditions. The host rocks for this deposit are primarily black carbonaceous shales containing varying amounts of sulfides and may be the controlling influence on the redox character of the ground water at this site. Note the high concentrations of As, Sb, and W, as well as the low concentrations of Au, in the water samples from this drill hole (Table 1). The water here is near neutral to alkaline with a pH range of 7.2 to 7.5. The temperature of the water from drill hole PV-287 is moderately elevated with a range of 30.4°C to 32.1°C. The high temperatures of the ground water at this location likely contribute to the increase in concentrations of dissolved constituents. These data indicate high mobility for As, Sb, and W, but low mobility for Au, in the high temperature and near neutral low-redox ground water here.

The analytical results on ground-water samples collected from drill hole PV-382 (Table 1), located up-gradient from the low grade deposit near Preble may represent the approximate local background concentrations for As, Sb, and W in ground water not associated with mineralized bedrock. Compared to this local background, the As, Sb, and W concentrations in ground-water samples from drill hole PV-287, which penetrates the low-grade gold deposit, are enriched ten to fifty fold.

Results for the sequential dissolution, extraction, and analysis of alluvial and bedrock material from several drill holes are shown graphically in Figs. 10–13. The distributions of Mn, Co, Fe, As, and Au in various phases of alluvial samples from drill hole R-313A, located above the Rabbit Creek disseminated gold deposit, are presented in Figs. 10A–E. For all the elements shown, a marked increase in concentration occurs in the alluvium at the approximate depth of the water table. The predominant chemical host for Mn and Co is the operationally defined manganese-oxide and amorphous iron-oxide fraction. For Fe and As the highest concentrations are found in the crystalline iron-oxide fractions of the alluvial material and for Au the highest concentration is found in the 4 N HCl leachate fraction. The alluvium from drill hole R-313A is described by Madden-McGuire et al. (1991) as muddy, sandy gravel to conglomerate, which varies in color from predominately light tan in the top 300 ft to yellow, brown, and red in the bottom 160 ft. It is important to note that the color change in the alluvial material occurs at the approximate depth of the water table. The increase in concentrations of trace metals and the color change in the alluvium at the water table boundary suggest water–rock reactions involving oxidation, precipitation, coprecipitation, and sorption. Similar observations of Au precipitation and sorption reactions are reported by Pitul'ko (1976), Plyusnin et al. (1981), Webster and Mann (1984), and Benedetti and Boulegue (1991).

Figs. 11A–C show the distribution of Mn, Co, and Sb in bedrock samples from drill hole SEE-367, located between the Chimney Creek and Rabbit Creek disseminated gold deposits. Pronounced increases in concentrations of all three elements are observed at the depth of the water table. The dominant chemical host for Mn and Co in bedrock samples collected near the water table is the manganese-oxide and amorphous iron-oxide fraction. For Sb, the highest concentrations are found in the crystalline iron-oxide fractions of bedrock samples collected near the water table and in the sulfide fractions of bedrock samples collected deeper in the drill hole (Fig. 11C). Analytical results on water samples collected from drill hole SEE-367 (Table 1) show As(III) to be the dominant arsenic species in the deeper part

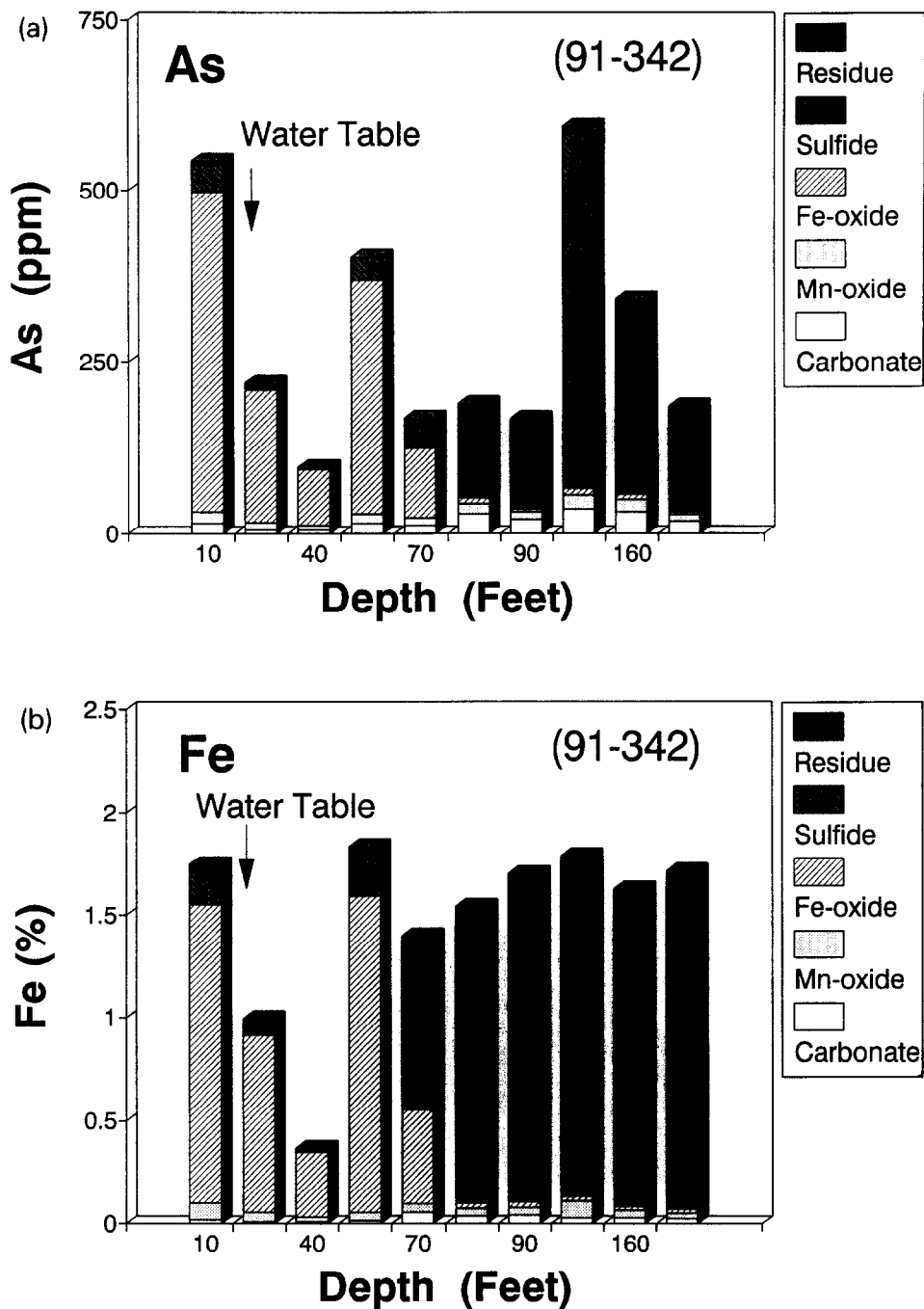


Fig. 12. Distribution of As (A) and Fe (B) in bedrock samples collected from drill hole 91-342, which is located over the Summer Camp disseminated gold deposit.

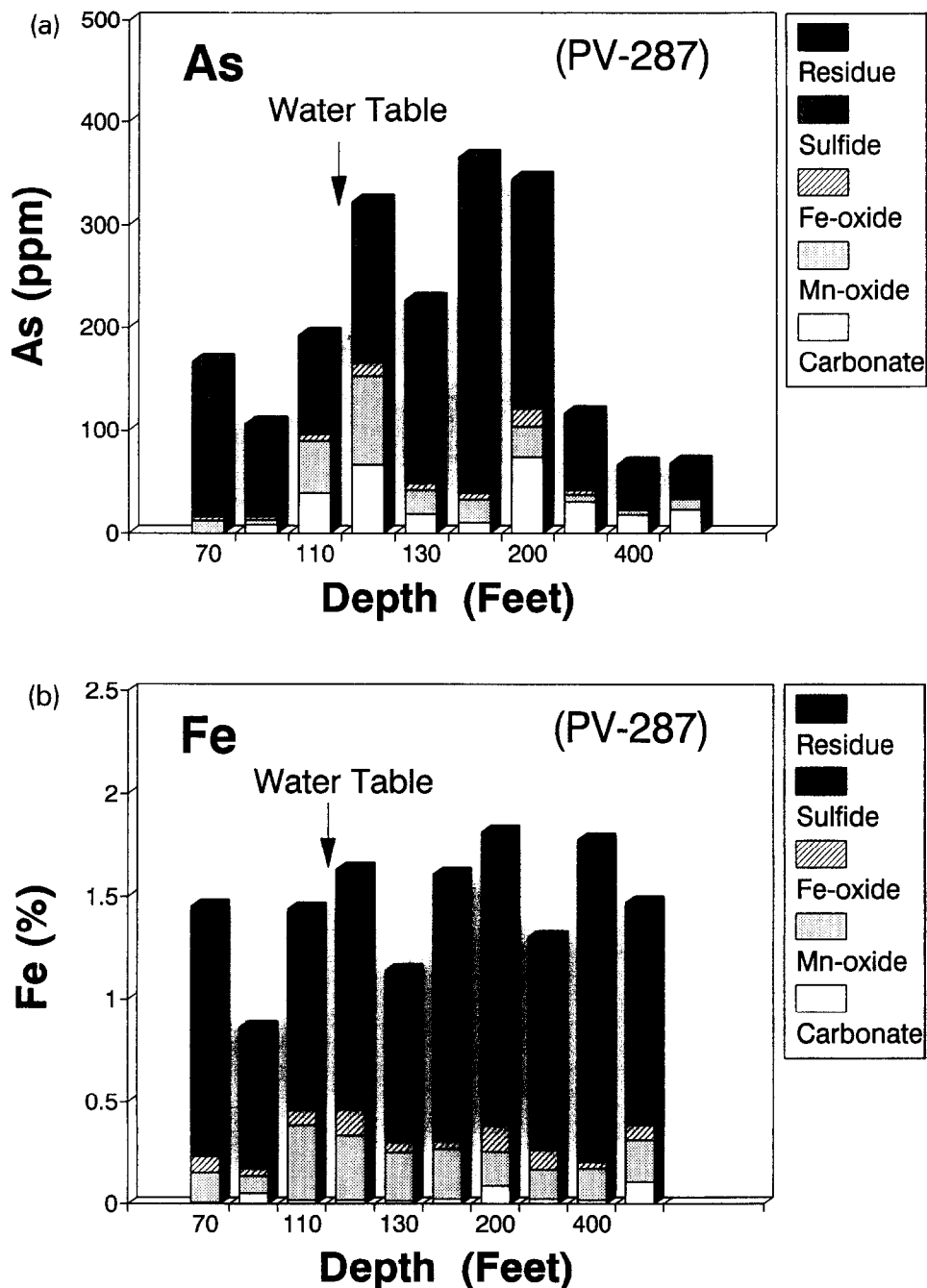


Fig. 13. Distribution of As (A) and Fe (B) in bedrock samples collected from drill hole PV-287, which is located over a buried disseminated gold deposit northeast of the Preble gold deposit.

of the local ground-water system. As(III) dominance indicates reducing conditions favorable for mobility of ore-associated elements such as Fe, As, Sb, and W. The dominant arsenic species in water samples collected in the vicinity of the water table, however, is As(V). As(V) dominance indicates oxidizing conditions, favorable for the oxidation and precipitation of elements such as Fe and Mn.

Figs. 12A and B show the distribution of As and Fe in bedrock samples from drill hole 91-342, located over the Summer Camp disseminated gold deposit. The dominant chemical phase of residence for As and Fe in the bedrock samples changes from the crystalline iron-oxide phase to a sulfide phase at a depth of about 80 ft. This is also the approximate depth where a change in the relative redox potential of the ground water, from oxidizing to moderately reducing, is indicated by the As(III) data (Table 1).

The distributions of As and Fe in bedrock samples collected from drill hole PV-287, located over a low grade disseminated gold deposit near Preble, are presented in Figs. 13A and B. The dominant chemical phase of residence for As and Fe in the bedrock samples, at all depths sampled, is the sulfide phase. There is no apparent increase in the concentrations of metals in the bedrock samples located near the water table. Reducing ground-water conditions at all depths are indicated by the negative E_h values and the arsenic species data in the water samples collected from drill hole PV-287 (Table 1). All of the dissolved arsenic at this site occurs as As(III), the reduced arsenic species. The extreme reducing conditions inhibits the oxidation of ore-associated elements in the ground water at this location and prevents significant precipitation of metals as oxides in the vicinity of the water table.

4. Summary

Background concentrations for Au in the ground water up-gradient from the buried deposits was less than 1 ng/L; near the deposits the Au values ranged from 1 to 140 ng/L; and, in drill holes penetrating mineralized rock, concentrations of Au in the ground water were as high as 4700 ng/L (Table 1). Highest concentrations of Au were found in ground-water samples where the measured E_h and the distribution of arsenic species indicated oxidizing redox potentials. Similarly, As, Sb, and W concentrations in the ground water near the deposits were significantly enriched relative to background concentrations in the ground water up-gradient from the deposits. In general, however, the highest concentrations of As, Sb, and W occurred in ground-water samples where the measured E_h and the distribution of arsenic species indicated reducing conditions.

Analytical results from this study suggest that Au and ore-associated elements are being mobilized from the concealed disseminated gold deposits in this area of Nevada and are being actively dispersed into the local ground-water system. Some of the elements are partly removed from solution through water-rock reactions, producing anomalous dispersion patterns in the alluvium away from the ore deposit at a depth coincident with the location of the present-day water table. The pH of the ground water in this area is neutral to alkaline and does not appear to have a controlling influence on the water-rock reactions here. However, the redox potential of the ground water around the buried deposits does appear to affect these reactions. Significant mobilization of Au was found under oxidizing conditions, whereas mobilization of As and Sb was enhanced under reducing conditions.

Significant increases in the concentrations of As, Sb, Co, Fe, and Mn were found in samples of alluvium from depths at and below the water table. Higher concentrations of these metals were also found in the analyses of the total digestion of samples; however, the sequential dissolution and extraction analyses showed that most of the metals were primarily concentrated in the operationally defined manganese-oxide and iron-oxide fractions of the samples. In one drill hole the maximum Au concentration was measured in the 4 N HCl leachate fraction of alluvial material from sample depths coinciding with the approximate elevation of the present-day water table. Up to a ten-fold increase in the concentration of Au was found in samples of alluvium collected at and below the water table compared to samples of alluvium collected above the water table. These analyses suggest that the metals may be occurring in the oxide coatings on the alluvial material probably resulting from sorption or coprecipitation reactions. Also, the apparent water-table boundary of the anomalous metals indicates that water-rock reactions between alluvial material and the ground-water systems around the buried disseminated gold deposits are on-going processes.

These results indicate that drill-hole hydrogeochemical surveys and sequential extraction analysis of overburden material may provide valuable data to exploration programs for discovering concealed disseminated gold deposits in Nevada and possibly elsewhere.

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