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Chapter 19

GEOLOGIC CONTROLS ON THE COMPOSITION OF NATURAL WATERS AND MINE WATERS DRAINING DIVERSE MINERAL-DEPOSIT TYPES

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INTRODUCTION

Sulfide-bearing mineral deposits formed in reduced conditions out of contact with an oxygenated atmosphere. When sulfides in the deposits are exposed by natural erosion or by mining to atmospheric oxygen and water, weathering of the sulfides can produce natural or mining-related acid-rock drainage. The prediction of water quality that results from mining and mineral processing activities has therefore become a high priority in the permitting of mining activities worldwide, in order to prevent the formation of or mitigate the environmental effects of deleterious drainage waters. In addition, estimating the compositions of natural waters that drained mineral deposits prior to mining is crucial to establish appropriate baseline environmental standards at mine sites.

There are a variety of techniques currently in use to predict the acidity or metal content of mine-drainage waters, most common of which are static and kinetic testing procedures. In static procedures such as acid-base accounting (White et al., 1997, 1999), the contents of acid-generating sulfide minerals from ores and wastes from a proposed mine are measured and balanced against the measured contents of acid-consuming minerals such as carbonates; based on this balance, the materials are determined to be acid generating or non-acid-generating. In kinetic tests such as column or humidity-cell tests (ASTM, 1996), samples of ores and wastes are allowed to react over a period of time under laboratory conditions with oxidized waters or moist air, and the pH and metal contents of the resulting leachates are then measured.

Although both static and kinetic methods are widely used to help predict the compositions of mine waters, they have several potential limitations. Most important of these are (1) whether the samples used in the tests adequately represent the range of mineralogic characteristics commonly present in complex mineral deposits, (2) whether the time scale and laboratory conditions of kinetic tests adequately reproduce the time scales and physical, geochemical, and biological conditions actually present in the mine, mine dump, or tailings impoundment environment, and (3) whether kinetic test leachate compositions accurately reproduce actual drainage quality.

Another approach to mine-drainage prediction that can be used to supplement the static and kinetic engineering tests is one in which the compositions of existing mine waters draining geologically similar deposit types in similar climates are measured empirically and then interpreted in a geologic and geochemical context. By evaluating the compositions of waters draining geologically comparable deposits in comparable climates, it is possible to place constraints on the potential ranges in composition of waters that might result from the development of a particular ore deposit. Such empirical examinations of existing drainage waters help overcome the issues of sample representation, adequacy of time scales, and accuracy of reproduction of natural conditions by laboratory experiments—the waters already are draining larger, more representative volumes of rock, and they are generated under field conditions and time scales.

Past studies that demonstrated the importance of geologic controls on mine-drainage compositions include those of Wildeman et al. (1974) in the Central City mining district, Colorado, and those of Wai et al. (1980) in the Bunker Hill mine, Coeur d'Alene district, Idaho. Results of both these studies showed that drainage compositions vary predictably within a mine (Wai et al., 1980) and across a district (Wildeman et al., 1974) as a function of deposit geology. However, in the time since these studies were carried out and prior to the early 1990s, a systematic examination of mine-drainage compositions across a spectrum of mineral deposit types, and within different ore types of given deposit types was generally lacking. Since the early 1990s, a number of studies have begun to examine both natural- and mine-drainage water compositions in the context of mineral-deposit geology (Ficklin et al., 1992; Plumlee et al., 1992, 1993a, b; Runnells et al., 1992; Smith et al., 1994; Price et al., 1995; studies in du Bray, 1995; Goldfarb et al., 1996, 1997; Eppinger et al., 1997; Kelley and Taylor, 1997).

This paper summarizes results to date of an ongoing empirical study examining the composition of mine waters and natural waters draining a broad spectrum of mineral deposit types, mineralogic zones within deposit types, and geologically similar mineral deposit types in different climates (Ficklin et al., 1992; Plumlee et al., 1992, 1993a; Smith et al., 1994). We include in this study data that we have collected and data compiled from the literature.

The results to date of this empirical study illustrate the many fundamental controls that mineral-deposit geology exerts, in combination with geochemical processes and biogeochemical processes, on the compositions of mine-drainage waters and natural waters draining unmined mineral deposits. Other important controls, such as climate, mining method used, and mineral processing method used, modify the effects mandated by deposit geology, geochemical, and biogeochemical processes. Our results show that, by interpreting empirical drainage data in a geologic context, it is possible to constrain the potential ranges in pH and ranges in metal concentrations of mine- and natural-drainage waters that may develop within different mineralogic zones, ore types, or alteration types in a given mineral deposit. Our results are not sufficiently precise that they can be used to quantitatively predict the exact compositions of water that will develop in a particular mine, mine dump, or tailings impoundment at a particular mineral deposit. Instead, the predictive capabilities provided by such an empirical approach should be only part of a comprehensive risk-based approach to environmentally responsible mineral-resource development employed by industry and regulators alike.

For general references on the geology of mineral deposits, the reader is referred to economic geology textbooks such as Guilbert and Park (1986), and to other compilations such as Cox and Singer (1986), Kirkham et al. (1993), du Bray (1995), and references contained therein. For a summary of the environmental geology characteristics of mineral deposits, see Plumlee (1999) and references therein.

SUMMARY OF DATA AND METHODS

Data on the compositions of mine- and natural-drainage water samples determined in this study and gathered from the literature are summarized by mineral-deposit type in the Appendix, and depicted graphically on Figure 19.1.

For the samples collected in this study, a detailed summary of the field sampling protocols is presented by Ficklin and Mosier (1999). For samples summarized from the literature, we primarily included in the Appendix data for samples that had been collected using generally similar methodologies to those we used. The pH values listed in the Appendix are field pH values, due to the potentially large shifts in pH that can occur between field collection and lab analysis. For chemical constituents, the Appendix generally lists samples that were filtered to at least 0.45 μm (and for some samples, to 0.1 μm) prior to chemical analysis. Based on results of sampling done early in this study (Smith et al., 1992) we concluded that, for most mine-drainage samples, the analytical results varied little between samples filtered to 0.45 μm and those filtered to 0.1 μm; hence, the inclusion of samples in the Appendix having different filter sizes imparts relatively little in the way of overall interpretational uncertainty.

Information on water types is also included in the Appendix. In compiling these data, we focused wherever possible on waters collected at adit openings, springs, open pit lakes, etc., in order not to introduce downstream or down-gradient compositional modifications such as dilution or oxidation. This way, we could examine as closely as possible the effects of deposit geology on drainage composition.

For a summary of environmental water analysis methods, the reader is referred to Crock et al. (1999). For nearly all samples included in the Appendix, ion chromatography was used to determine the concentration of sulfate and (where done) other anions. For cations and trace metals, the data in the Appendix reflect a variety of methods, including flame and (or) graphite furnace atomic absorption spectrophotometry (AA), inductively coupled-plasma atomic emission spectroscopy (ICP-AES), and inductively coupled-plasma mass spectrometry (ICP-MS). Based on the results of data collected in our study, we have found general reproducibility (to within approximately ± 10–25%) between the different analytical methods we used (K. Smith, G. Plumlee, unpub. data).

Another challenge in interpreting data collected by multiple studies is presented by the concentration units used by the different studies. For the data we collected as part of this study, sulfate, fluoride, chloride, alkalinity, and ferrous iron concentrations were determined in mg/l concentration units; all other major cations, trace metals, and metalloids were measured in parts per million (ppm) or parts per billion (ppb) units. In contrast, the concentrations of major cations, trace metals and metalloids were measured in some other studies (such as Alpers and Nordstrom, 1991) on a volume basis and presented in mg/l or μg/l units; we have noted in the Appendix all samples measured in these units. For the graphically-based interpretations used in this study (such as Fig. 19.1), we have assumed that mg/l units are equivalent to ppm, and that μg/l units are equivalent to ppb. Although this assumption is appropriate for relatively dilute waters, it becomes less so for the more concentrated waters such as those from Summitville, Colorado or Iron Mountain, California (Alpers and Nordstrom, 1991). However, given the log scale used in all of the plots, the uncertainties introduced by our assumption does not make a substantial difference in our results or interpretation. Nonetheless, given the potential uncertainties introduced by differences in analytical methodologies and concentration units, we will restrict our interpretation of compositional differences between samples to the ±50% level.

The data on both mine-drainage and natural-drainage waters compiled to date span a broad range of pH values (from less than zero to greater than 8) and a broad range in content of a variety of dissolved metals and other species (depending upon the element, levels from < 1 μg/l to tens of thousands of mg/l; Fig. 19.1). In order to help interpret variations in drainage water chemistry between different deposit types, we have developed a classification scheme based on the pH and the sum of the base metals Zn, Cu, Pb, Cd, Co, and Ni (Fig. 19.2; Plumlee et al., 1992). Although Fe, Al, and Mn are typically the most abundant metals in the majority of mine- and natural-drainage waters, differences in the sum of base metals allow us to differentiate between different geologic controls on water composition that we would otherwise not be able to differentiate on the basis of concentrational variations in Fe, Al, or major cations. We have termed such plots Ficklin diagrams in honor of our late colleague, Walter Ficklin. As can be seen from the plots on Figures 19.1 and 19.2: acid-rock drainage can be entirely natural and not related to mining activities; not all natural or mining-related rock drainage is acidic; and not all natural- or mine-drainage waters must be acidic to transport significant quantities of some dissolved metals.

SUMMARY OF IMPORTANT CONTROLS ON DRAINAGE COMPOSITION

Geochemical and biogeochemical controls

In order to understand the controls of mineral-deposit geology on drainage composition, it is first necessary to discuss briefly the geochemical and biogeochemical processes that generate and neutralize acid drainage (summarized by Nordstrom and Alpers, 1999, and references therein). Microbially mediated pyrite oxidation is generally the initial step in the process, and results in the formation of sulfuric acid and ferrous iron. At pH values greater than approximately 6, ferrous iron oxidizes very rapidly to ferric iron; at lower pH values, bacterial catalysis is required for this reaction to proceed. If the waters move out of contact with atmospheric oxygen or oxygenated ground waters, then the bacterial oxidation of iron can still occur only as long as limited concentrations of dissolved oxygen remain in the waters. Ferric iron is a

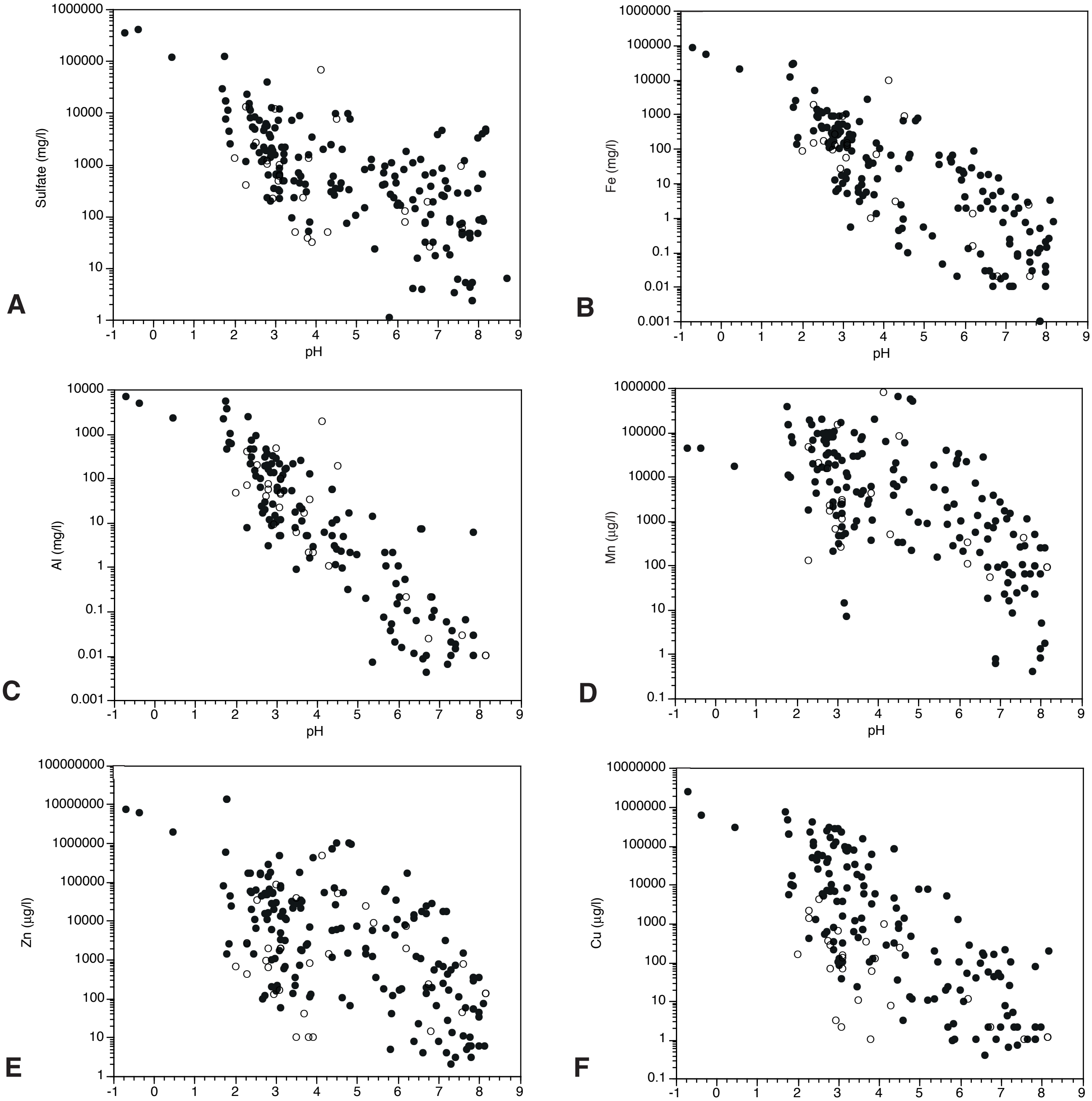

FIGURE 19.1—Plots of dissolved species concentrations of mine-drainage waters (solid circles) and natural waters draining unmined mineralized areas (open circles) as a function of pH. Data used to construct the plots are summarized in the Appendix. For the metal-pH plots, and all subsequent plots in this paper showing metal concentrations, we assume that ppm and mg/l concentration units are equivalent, and that ppb and µg/l concentration units are equivalent; see Summary of Data and Methods section for discussion. A. Sulfate; B. Total iron; C. Aluminum; D. Manganese; E. Zinc; F. Copper. Note differences in scale of the concentration axis between the plots.

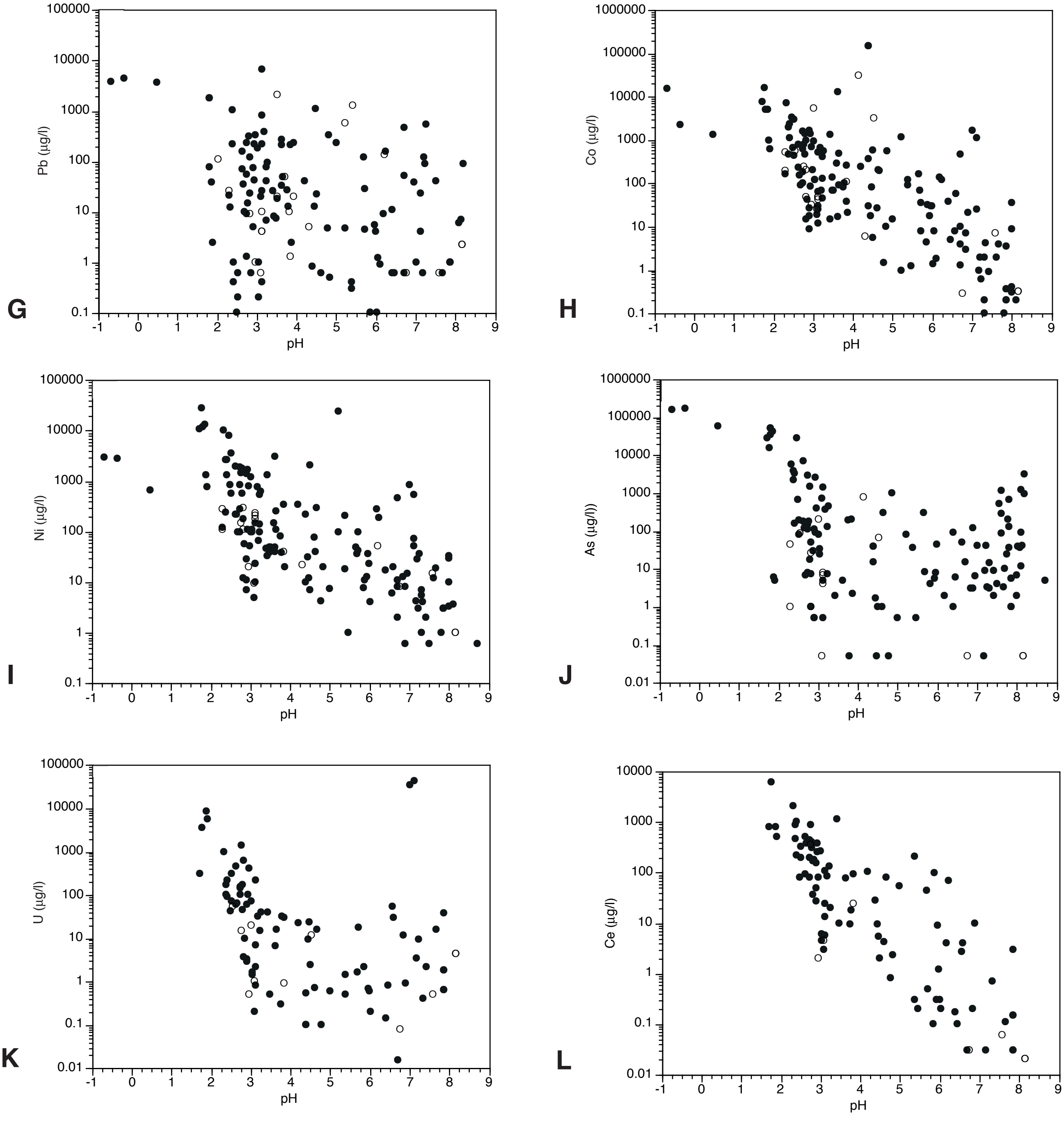

FIGURE 19.1 Continued—Plots of dissolved species concentrations of mine-drainage waters (solid circles) and natural waters draining unmined mineralized areas (open circles) as a function of pH. Data used to construct the plots are summarized in the Appendix. G. Lead; H. Cobalt; I. Nickel; J. Arsenic; K. Uranium; L. Cerium.

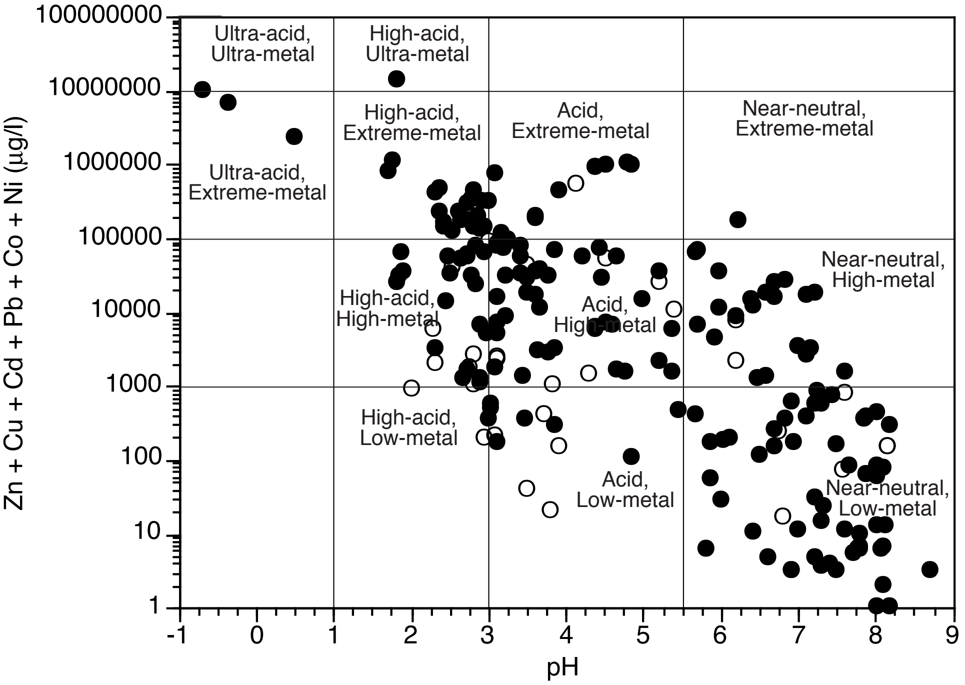

FIGURE 19.2—Ficklin diagram showing the sum of dissolved base metals Zn, Cu, Cd, Pb, Co, and Ni in mine (closed circle) and natural (open circle) waters draining diverse mineral-deposit types. The boundaries and names of metal bins were originally proposed by Plumlee et al. (1992) to help classify different drainage compositions. For the plot, we assume that that ppb and µg/l concentration units are equivalent; see discussion in Summary of Data and Methods section.

very effective oxidant, and when it reacts with iron sulfides and a variety of other sulfides, it can generate significant quantities of acid plus reduced iron, which is then reoxidized by bacterial catalysis. Metal sulfides with a metal:sulfur ratio ≤ 1 (such as galena, sphalerite, and covellite) do not generate acid when they are oxidized by atmospheric oxygen, but do when they are oxidized by ferric iron (Smith et al., 1994; Nordstrom and Alpers, 1999; Plumlee, 1999).

Once acid drainage waters form, there are a variety of processes that affect their compositions. The acid waters can react with carbonate or some aluminosilicsate minerals in the deposit or its host rocks, which can shift pH to less acidic values. Typically, calcite and aragonite are the most reactive carbonate minerals, and therefore are most effective at consuming acid. Other carbonates such as rhodochrosite, dolomite, and magnesite are much less reactive, as are most aluminosilicates, and therefore are much less effective at neutralizing acid in drainage waters. If the waters move out of contact with atmospheric oxygen, they can build up elevated levels of ferrous iron; when they reach the ground surface again, oxidation of the ferrous iron to ferric iron will result.

Saturation with various amorphous or crystalline phases can limit concentrations of some major constituents in the drainage waters. Studies of diverse mine drainages (see Nordstrom and Alpers, 1999) have shown that, at pH values above approximately 2–3, ferric iron concentrations are restricted by the formation of poorly crystalline to amorphous iron phases such as ferrihydrite (a hydrous ferric oxide), jarosite (a potassium-iron hydroxysulfate), or schwertmannite (a ferric hydroxysulfate) (Nordstrom and Alpers, 1999; Smith, 1999); these are the orange to yellow to brown precipitates that commonly line mine-drainage stream beds. Similarly, studies have shown that, at pH values above 4.5–5, aluminum concentrations are limited by the formation of aluminum oxyhydroxysulfates such as basaluminite (Nordstrom and Alpers, 1999); these minerals (typically seen as white coatings on stream beds) most commonly precipitate via pH increases resulting from dilution by non-acidic ground or surface waters. At pH values greater than 5, dissolved ferric iron concentrations are held at very low levels by the ferric phases mentioned previously. However, in less acidic to near-neutral pH waters with low dissolved oxygen, ferrous iron can reach relatively high levels in solution; when the waters come into contact with the atmosphere, the ferrous iron oxidizes rapidly to ferric iron, leading to the precipitation of one of the ferric phases mentioned previously. Hydrous manganese oxide minerals tend to form at quite high pH values (typically > 8); however, bacterial mediation can lead to precipitation of manganese phases at pH values below 6–7. Precipitation of hydrous oxide minerals in mine-drainage streams produces hydrogen ions as a result of metal hydrolysis reactions (Garrels and Christ, 1965; Nordstrom and Alpers, 1999). As a result pH decreases of as much as several pH units downstream from springs or adits can be quite common. Hence, mine- and natural-drainage waters can have near-neutral pH values but can still generate acid once they are liberated into the environment.

Chemical speciation programs such as WATEQ4F (Ball and Nordstrom, 1991; summary in Alpers and Nordstrom, 1999) can be used to calculate mineral saturation indices, which can be used to help constrain the mineral phases that may be controlling drainage compositions. Waters have a thermodynamic tendency to precipitate phases with calculated saturation indices greater than 0, and a thermodynamic tendency to dissolve phases with calculated saturation indices less than 0. Other factors, such as kinetics, or the presence or absence of the mineral in contact with the water will also influence whether a mineral dissolves or precipitates. We used WATEQ4F to calculate the chemical speciation and solid-phase saturation indices of a number of drainage compositions (see Appendix) spanning much of the spectrum of pH values shown on Figures 19.1 and 19.2; some results of these calculations are shown on Figure 19.3. All but the highest-pH waters (from the Carlton Tunnel, pH 7.7; see Appendix) are calculated to be near saturation or supersaturated with one or more of the jarosite solid-solution end members, indicating that jarosite may be an important phase influencing iron concentrations in these waters. Ferrihydrite, in contrast, is undersaturated in the most acidic waters, suggesting that it is not influencing ferric iron concentrations at pH values below approximately 3–4. All but the Carlton Tunnel waters are very close to saturation with jurbanite (Fig. 19.3), an aluminum hydroxysulfate; these calculations suggest that aluminum concentrations in solution may be influenced by aluminum-bearing phases at pH values even lower than 4.5–5, as is commonly presumed (Filipek et al., 1987; Nordstrom and Alpers, 1999). Silica concentrations are likely to be limited by one of the silica phases, although the calculated saturation indices indicate that the concentration-limiting phase may change with pH (Fig. 19.3). Although not shown on Figure 19.3, the calculations indicate that at least some drainage waters with pH values greater than 6 are calculated to be near saturation or supersaturated with rhodochrosite (the calculations assume that concentrations of dissolved Mn^{2+} and Mn^{3+} are in equilibrium with measured dissolved oxygen concentrations). In addition, the Carlton Tunnel waters are calculated to be near saturation with a variety of aluminosilicate phases such as zeolites or feldspars. Carbonates such as calcite, aragonite, or rhodochrosite may play a role in influencing water compositions; however, zeolites and feldspars are unlikely to influence solution compositions in higher-pH drainage waters (D.K. Nordstrom, written commun., 1998).

The concentrations of metals such as lead, copper, zinc, cadmium, and nickel, and metalloids such as arsenic are variably controlled by aqueous complexation (Fig. 19.4), coupled with sorption onto particulates (most commonly the hydrous ferric or hydrous aluminum oxides; Smith, 1999). In the acidic drainage waters, the speciation calculations indicate most metals occur as the simple metal ions or as sulfate complexes (Fig. 19.4). In near-neutral pH waters, carbonate and hydroxide metal complexes are calculated to become more important than the metal ions or sulfate complexes. Precipitation of carbonate minerals such as cerussite (Pb) and smithsonite (Zn), or malachite and azurite (hydrous Cu-carbonates) may limit concentrations of these metals in near-neutral to alkaline waters. Arsenic and some metals such as molybdenum are commonly present as oxyanion species.

The extent of sorption onto particulates is a function of the pH of the waters, the particular metal, the concentrations of aqueous complexing agents (which compete for the metals with the sorption sites on the particulates), and the concentrations of the metals relative to the amounts of particulates. Smith et al. (1992, 1993) demonstrated that sorption is largely mediated by particulates suspended in the water column, and not by bed sediments. In general, the effectiveness of sorption with increasing pH is As > Pb > Cu > Zn > Cd, Ni (Fig. 19.5). Arsenic and lead are most effectively sorbed at quite acidic pH values (in addition to Fig. 19.5, note the precipitous drop in arsenic in all drainages at pH 2–3 shown on Fig. 19.1J), whereas Zn, Cd, and Ni are partially to minimally sorbed only at near-neutral pH values in waters with

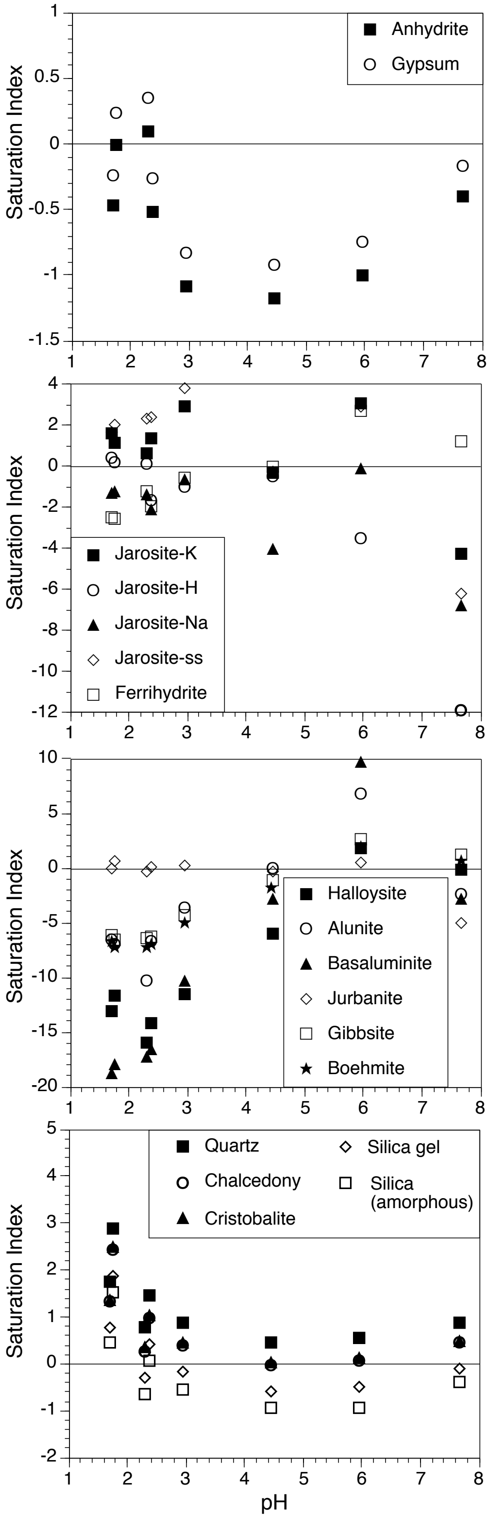

FIGURE 19.3—Calculated saturation indices for various Colorado mine-drainage waters sampled as part of this study. Samples include, in order of increasing pH: Blackstrap, Son-of-Blackstrap, Reynolds adit, Chandler Adit (all from Summitville); Yak Tunnel (Leadville); Bandora (Silverton); and Carlton Tunnel (Cripple Creek). See sample descriptions in the Appendix for the mineral deposits drained by these waters.

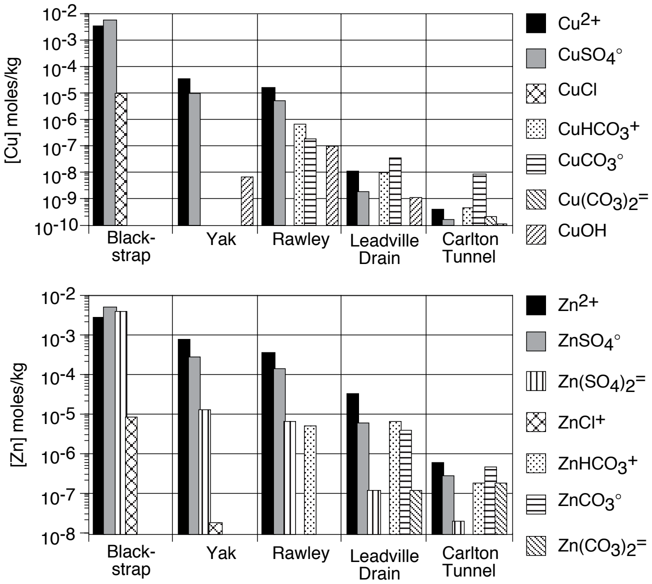

FIGURE 19.4—Calculated concentrations (using WATEQ4F) of copper (upper) and zinc (lower) complexes for several Colorado mine-drainage waters sampled as part of this study (Appendix). pH values increase from left to right: Blackstrap—pH 1.8; Yak—4.4; Rawley—6.0; Leadville Drain—pH 7.2; Carlton—pH 7.7.

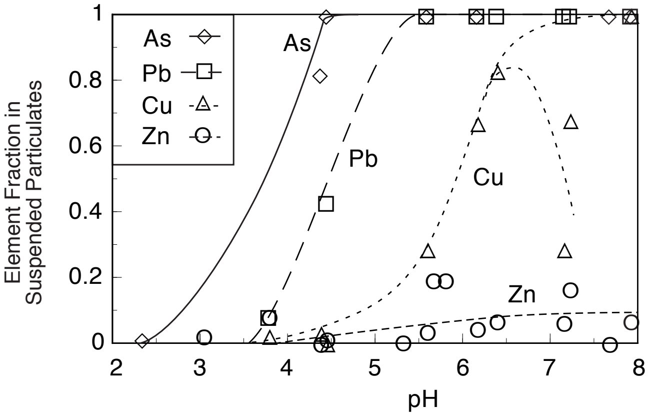

FIGURE 19.5—Plot showing fraction of As, Pb, Cu, and Zn associated with suspended particulates as a function of pH of selected mine-drainage waters sampled in the early phases of this study. A fraction of 1 means that the element is entirely associated with particulates greater than 0.1 µm in size, whereas a fraction value of 0 means that the element is not associated with particulates greater than 0.1 µm. Cadmium and nickel are essentially in solution (not associated with particulates) in all drainage waters shown on the plot. Figure modified from Smith et al. (1992)

small to moderate amounts of suspended particulates. Some elements such as As, and Mo tend to desorb at near-neutral or higher pH values due to their presence as oxyanions, although As desorption in higher-pH drainage waters is not observed in the samples shown on Figure 19.5, it is indicated by the elevated dissolved As concentrations in samples with pH values greater than ~ 7 shown on Figure 19.1. Metals such as U, Cu, and Pb also tend to desorb at near-neutral or higher pH values due to increased competition from complexing agents such as aqueous carbonates, which help keep the elements in solution. For example, the spread of Pb concentrations with increasing pH shown on Figure 19.1G and the increase in U concentrations with increasing pH above 5–6 (Fig. 19.1K) likely reflect desorption due to lack of particulates or increased competition from complexing agents.

Other geochemical processes that affect drainage composition include evaporation and, should sufficient evaporation occur, precipitation of secondary sulfate salts (Nordstrom and Alpers, 1999). Evaporation can be important in open-pit mines, mine dumps, tailings, and underground mine workings. It can lead to increased metal concentrations and, in acid waters, decreased pH. Secondary salts that form from evaporation (Nordstrom and Alpers, 1999) are typically soluble hydrous sulfates of a variety of metals, including iron (melanterite, römerite, and rhomboclase), aluminum (halotrichite), calcium (gypsum), magnesium (pickeringite), copper (chalcanthite, brochantite), and zinc (goslarite). A variety of salts can also form directly on sulfides in mine workings and mine dumps through the attack of humid air on the sulfides. No matter how they form, these metal salts can store acid and metals in the solid form, and dissolve readily during the next wet period such as snow-melt or rainstorm runoff.

Geologic controls

When grouped according to the geologic characteristics of the deposits they drain, the water compositions depicted on Figures 19.1 and 19.2 generally span a much smaller range of pH values and metal contents (Fig. 19.6). As will be demonstrated in the discussions that follow, there are a variety of geological features of mineral deposits that control the composition of natural- and mine-drainage waters, including: the content of acid-generating pyrite and other iron sulfides; the content of sulfides other than iron sulfides; the content of carbonates and other acid-consuming minerals in the deposit; the rock types hosting the deposit; the types of alteration present in the deposit host rocks; the nature of the ores (vein, disseminated, massive); the reactivity of both acid-generating and acid-consuming minerals (a function of grain size and trace-element content of the minerals); the trace-element content of the deposit and host rocks; and, the extent of pre-mining oxidation. In general, the trend of increasing metal content with decreasing pH depicted on Figure 19.6 reflects greater amounts of pyrite and other sulfide minerals associated with the deposit, and a smaller content of carbonates and other minerals that consume acid. Some deposits can be carbonate-rich but can still generate acidic waters (see, for example the acidic waters draining carbonate-rich deposits on Fig. 19.6) if the acid-buffering carbonates are physically separate from the acid-generating sulfides so that the waters interact with the sulfides and not the carbonates, or if a reaction barrier of iron hydroxides or other minerals protects the carbonates from reaction with the acid waters. Greater amounts of

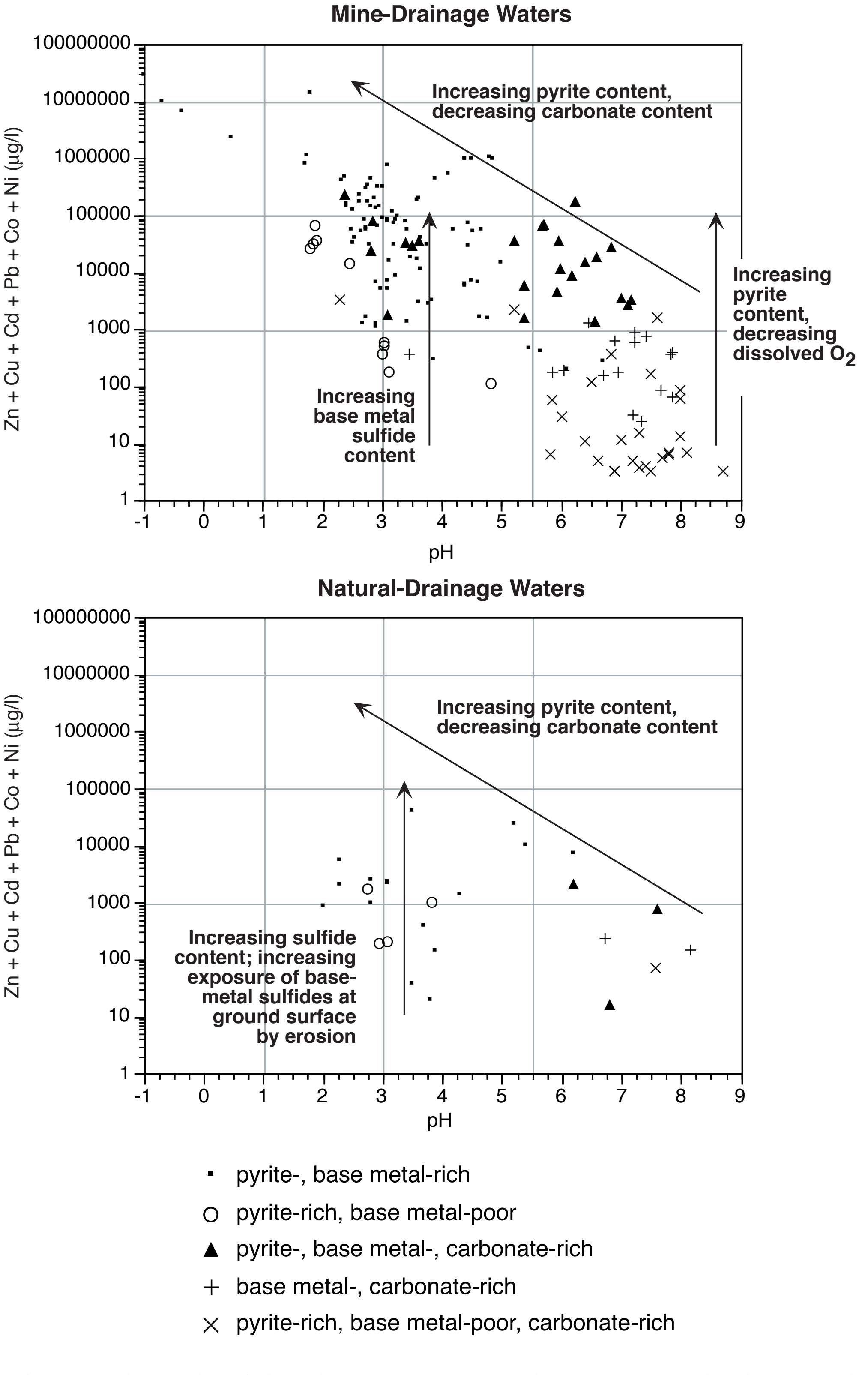

FIGURE 19.6—Ficklin diagrams showing groupings of mine-drainage (upper) and natural-drainage (lower) samples listed in the Appendix according to pyrite content, base-metal sulfide content, and carbonate content of the mineral deposits drained by the waters.

pyrite or base-metal sulfides (such as chalcopyrite and sphalerite) also led to greater dissolved base-metal contents in waters draining deposits with generally similar acid-neutralizing capacities.

Concentrations of individual elements in the drainage waters in part reflect the elements' abundances in the deposits drained by the waters. Due to the abundance of sphalerite in many metal deposits, zinc is the predominant metal (other than Fe, Al, and Mn) in most drainage waters; however, copper-rich, sphalerite-poor deposits tend to have copper-dominant drainage waters, arsenic-rich deposits have arsenic-rich waters, and so on. Due to its limited tendency to sorb onto particulates, zinc is generally the predominant metal in drainage waters with near-neutral pH values. The greatest dissolved zinc values we have measured in near-neutral drainage waters occur in waters draining pyrite- and sphalerite-rich ores with abundant carbonate minerals to buffer pH, but that have limited dissolved oxygen (which prevents the formation of iron particulates that would otherwise sorb more of the dissolved zinc).

For natural waters that drain unmined mineral deposits, the content of dissolved base metals increases at a given pH with increasing base-metal sulfide content of the deposit. In addition, deposits with base-metal sulfides exposed at the ground surface by rapid erosion or glaciation (the natural analogs to the exposure of fresh sulfides by mining activity) commonly have natural-drainage waters with similar pH values but greater dissolved base-metal concentrations than natural waters draining deposits with no sulfides exposed at the ground surface.

A number of mines that are currently in production are developed in mineral deposits that have undergone extensive to complete oxidation during weathering prior to mining. Especially common in dry climates where water tables are deep, this oxidation removes the acid-generating sulfide minerals and leaves behind non-acid-generating oxides, hydroxides, and carbonates. Thus, all deposit types, regardless of their original sulfide content, that have been completely oxidized during pre-mining weathering will most likely generate non-acidic waters with generally low concentrations of metals. However, even small pockets of sulfide-rich, carbonate-poor rocks that remain after weathering can be sufficient to generate acid-mine waters in an otherwise oxidized deposit.

Climate and mining method controls

As can be seen from the Appendix, and as will be shown in the following discussions, climate and the methods used during mining and mineral processing can affect drainage compositions, though mostly within the compositional ranges mandated by geologic characteristics. For example, waters draining mine dumps and those that form in open pits tend to have somewhat more acidic and metalliferous compositions than those draining mine workings, due to the increased surface area of sulfides exposed to weathering and increased opportunities for (a) atmospheric oxygen access to the sulfides and (b) evaporative concentration. Waters draining sulfide-rich tailings impoundments can be quite acidic and metal-bearing even in deposit types with high carbonate contents (see Fig. 19.6, acidic waters draining pyrite- and carbonate-rich deposits). The milling and tailings disposal process can concentrate the pyrite sufficiently that acid generated by sulfide oxidation overwhelms the acid-neutralizing capacity of carbonates in the tailings; for example, physical sorting of dense sulfides from less dense carbonates may create sulfide-rich zones in the tailings that have high acid-generating potential. Similarly, storm waters draining sulfide-rich, carbonate-bearing mine waste dumps may potentially be acidic, if the acid waters formed by the dissolution of soluble salts growing on sulfide surfaces flush so rapidly from the dumps as to not have time to react with carbonate minerals in the dumps.

Mineral deposits commonly generate less drainage in arid and semi-arid climates than in wet climates. For example, in arid climates, many mines are developed above deep water tables, and many mine dumps may not drain except for short periods after storms. The data in the Appendix indicate that, for acid-generating deposit types, those drainage waters that do occur in arid climates tend to be more acidic and metalliferous than those in wetter climates due to the effects of increased evaporation and the decreased potential to be diluted by non-mineralized ground and surface waters.

MINE- AND NATURAL-DRAINAGE SIGNATURES OF DIVERSE MINERAL-DEPOSIT TYPES

Although mineral deposits can be typed according to overall similarities in their geologic characteristics, geologic setting, and mode of formation, they typically have complex variations in mineralogy, alteration, and (or) wallrock within a given deposit. Thus, the grouping of mine- and natural-drainage waters based on similar geologic characteristics alone (Fig. 19.6) is insufficient to characterize the possible range of drainage compositions that can occur within a geologically complex deposit type. Instead, drainage compositions must be measured and summarized for each ore type, mineralogic zone, alteration type, and (or) host rock type for a given mineral deposit type. In the following discussion, we will use Ficklin plots to show how drainage compositions vary as a predictable function of deposit type and location within a deposit type. We will start our discussion with the deposit types having geologic characteristics in their main ore zones that are favorable for the generation of the most acidic waters, and shift progressively to those deposits having ores that are likely to generate less acidic and metal-bearing waters. However, even in the deposit types most likely to generate highly acidic waters, we will show that a variety of drainage compositions, including those that are less acidic and metalliferous, can occur within different parts of the deposits.

Volcanogenic massive sulfide (VMS) deposits

Syngenetic VMS deposits result from the discharge of hydrothermal mineralizing fluids onto the ocean floor, a process analogous to that observed today where sub-oceanic hot spring systems, known as "black smokers," form chimneys and other sulfide deposits on the ocean floor. For summaries of the geologic characteristics of this type, the reader is referred to reviews such as Franklin (1993), Slack (1993), Taylor et al. (1995), Evans et al. (1995), and references contained therein.

The deposits form in or near areas of subaqueous volcanism, which provides the heat source for the hydrothermal systems, and are commonly associated with volcanic or metamorphosed volcanic rocks. Volcanic-hosted VMS deposits include Cyprus-type, which occur in basaltic volcanic rocks, and Kuroko-type, which occur in andesitic to rhyolitic volcanic rocks (Franklin, 1993). In contrast, Besshi-type VMS deposits occur in sequences of predominantly sedimentary rocks such as turbidites and black shales (or their metamorphosed equivalents, graphitic schists), with some interbedded volcanic rocks such as basalts or intrusive rocks such as diabase sills.

Variations in metal contents permit further differentiation of VMS deposits. Franklin (1993) differentiates copper-zinc (Cu > Zn content) and zinc-lead-copper (Zn > Pb > Cu content) subtypes. Deposits of the zinc-lead-copper subtype are associated with silicic volcanic rocks. Blackbird-type deposits (named after the Blackbird mining district, Idaho) are cobalt- and arsenic-rich Besshi-type deposits.

VMS deposits are typically zoned, with pyrite, pyrrhotite, and chalcopyrite forming in the hotter, sub-seafloor and near-vent portions of the deposits. These "yellow ores" grade upward and outward into sphalerite- and (in the case of the zinc-lead-copper-subtype deposits) galena-rich ores ("black ores") that were deposited on the ocean floor. As implied by their name, VMS deposits can consist of massive ore lenses that are predominantly to nearly entirely composed of sulfides. The wallrocks present around the sub-seafloor feeder zones of the deposits are typically altered to chlorite-sericite-pyrite or chlorite-rich assemblages. Some carbonate minerals may be present in the surrounding host rocks, especially in sediment-hosted Besshi-type deposits.

Drainage-water compositions

Geologic controls on the composition of mine drainage waters from VMS deposits are summarized by Taylor et al. (1995) and Goldfarb et al. (1996). As shown on Figure 19.7A, mine-drainage compositions measured in VMS deposits span a large range in pH and metal contents, reflecting geologic controls, the effects of evaporation, and climate. Mine waters from the Iron Mountain, California, Kuroko-type deposit are the most acidic and metalliferous ever measured (Alpers and Nordstrom, 1991; Nordstrom and Alpers, 1999), with field pH values as low as -3.5 and dissolved contents of Fe, Al, Zn, and Cu as high as tens of grams per liter. These extreme compositions most likely reflect several factors. First, the mine waters likely flow through the massive sulfide lenses and do not interact with any potentially acid-consuming wallrock minerals. Second, the temperatures in the mine stopes are very hot (possibly as high as 60–70°C) and water temperatures reach as high as 46–47°C (D.K. Nordstrom, written commun., 1998), due to heat generated by exothermic pyrite oxidation. Thus evaporative concentration of the mine waters is likely to be important (Alpers and Nordstrom, 1991). Third, the climate at the West Shasta district is relatively dry, but with a distinct annual wet-dry

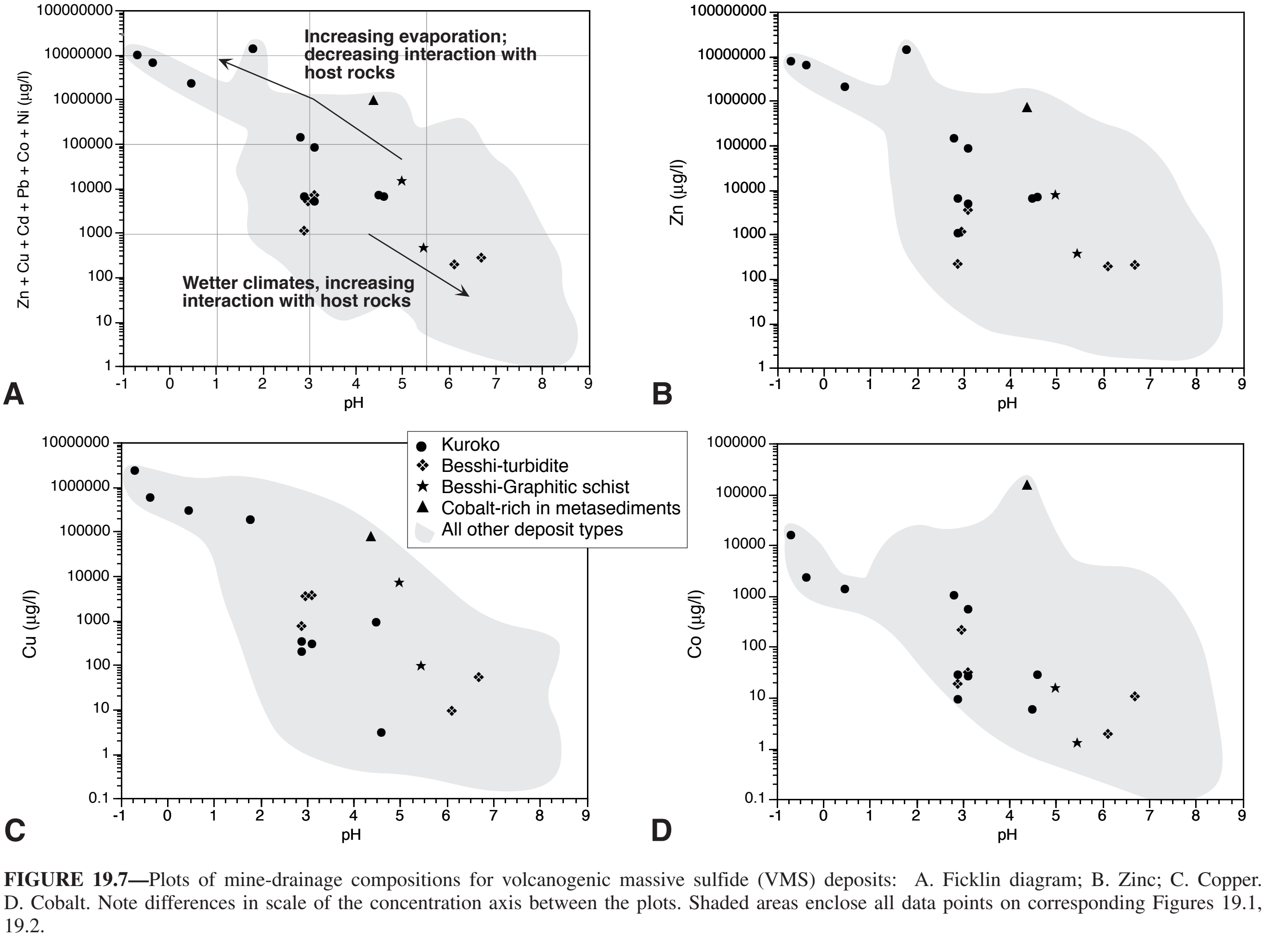

FIGURE 19.7—Plots of mine-drainage compositions for volcanogenic massive sulfide (VMS) deposits: A. Ficklin diagram; B. Zinc; C. Copper. D. Cobalt. Note differences in scale of the concentration axis between the plots. Shaded areas enclose all data points on corresponding Figures 19.1, 19.2.

cycle, which also enhances periodic evaporative concentration of the mine waters.

Mine-water compositions measured in some portions of Iron Mountain (C.N. Alpers, oral commun., 1994), as well as in other Kuroko-type VMS deposits such as Holden, Washington (Kilburn and Sutley, 1997) are typically quite acidic and metalliferous, although less so than the extremely acid waters at Iron Mountain (Appendix). The waters with less extreme acid pH values likely reflect buffering by reactions with aluminosilicate minerals in the deposit host rocks. The Holden mine site is also located in a wetter climate than Iron Mountain, which may lead to greater recharge of ground waters into the mine workings, and may preclude high amounts of evaporation that would lead to extreme concentrations of acid and metals in solution.

Although we have not included in our summary mine-drainage data for Cyprus-type VMS deposits, it is likely that the water compositions are generally similar to those of Kuroko-type VMS deposits. Waters that interact with the intermediate to basaltic-composition rocks hosting Cyprus deposits may be somewhat less acidic than those draining Kuroko-type deposits, due to the increased reactivity and acid-buffering capacity of the basaltic host rocks.

The limited data we have collected on waters draining Besshi-type deposits hosted by graphitic schists in the Great Smoky Mountains of Tennessee indicate a somewhat higher pH and lower overall metal content than for waters draining Kuroko-type deposits. This may result from both the partly disseminated nature of the ore within the graphitic schists and the wetter climate. The data collected by Goldfarb et al. (1996) for turbidite-hosted, Besshi-type VMS deposits in Prince William Sound, Alaska, show a trend to significantly higher pH values and lower metal contents than for waters draining the Kuroko-type VMS deposits. Goldfarb et al. (1996) attributed the higher pH and lower metal contents to the significantly wetter and lower-temperature climate of the area.

Another factor that may affect drainage pH in some VMS deposits is the presence of carbonate minerals in the deposit host rocks. In such deposits, mine waters that interacted significantly with carbonate-bearing host rocks might be expected to have near-neutral pH values but elevated levels of zinc, copper, and cadmium (see for example the distribution of data points marked by triangles on Figure 19.6, which depict drainage compositions of pyrite-rich, base metal-rich and carbonate-rich deposit types).

The relative abundances of metals such as Zn and Cu in the VMS drainage waters in part reflect (1) the overall chemical composition and mineralogy of the deposits, (2) the mineralogic zones within the deposits, and (or) (3) seasonal variations stemming from flushing of salts from the mine workings. For example, the Co- and Cu-rich massive sulfides of the Blackbird mine, Idaho (data summarized by Evans et al., 1995, and McHugh et al., 1987), have exceptionally high levels of Co in the drainage waters (Fig. 19.7D). Copper-rich stockwork feeder zones of VMS deposits generate drainage waters that are enriched in Cu relative to Zn, whereas waters that drain the overlying sphalerite-rich ore zones of the deposits likely have enrichments of Zn over Cu in the waters. Alpers et al. (1994) have shown that seasonal flushing of soluble salts from the mine workings at Iron Mountain results in significant decreases in Zn/Cu due to the selective dissolution of copper-bearing melanterite during the flush.

High sulfidation epithermal (quartz alunite epithermal) deposits

High-sulfidation epithermal, or quartz-alunite epithermal, deposits are Au-Cu-Ag deposits that form in close spatial and temporal association with shallow (within the upper several km of the Earth's crust) silicic volcanic or intrusive centers (Fig. 19.8). At Summitville, Colorado, for example, the deposits are hosted by a 22 Ma quartz latite volcanic dome, and were formed during the late stages of the dome-forming cycle of volcanism. Other examples include Red Mountain Pass, Colorado; Goldfield and Paradise Peak, Nevada; Mount Macintosh, British Columbia, Canada; and Julcani, Peru (see references to studies of these deposits contained in Plumlee et al., 1995c). The deposits are characterized by intense acid leaching and alteration of the deposit host rocks that were generated by magmatic gas condensates prior to ore-stage mineralization. In general, the cores of the deposits are characterized by intersecting zones of silica alteration (where all constituents of the host rock except silica were removed by the leaching), flanked by thin zones of quartz-alunite-pyrite and quartz-kaolinite alteration. In some of these deposits such as Summitville, the silica alteration is vuggy, due to the complete acid leaching of original feldspar phenocrysts from the volcanic host rock. The core of intensely altered rock is surrounded proximally by large volumes of argillically altered rock (the rock is altered to clays and pyrite), and a distal zone of propylitically altered rock (altered to contain epidote, chlorite, some pyrite, and calcite) (Fig. 19.8). Subsequent to the intense acid alteration, hydrothermal fluids, whose flow was focused primarily along the higher-permeability vuggy silica zones, deposited sulfide-rich assemblages containing pyrite, native sulfur, enargite (a copper-arsenic sulfosalt), chalcocite and covellite (copper sulfides), and native gold in the central portions of the deposits, grading upward and outward into sphalerite-, galena-, and barite-rich assemblages in some deposits. At depth beneath the acid-altered rocks, the hydrothermal fluids typically deposited chalcopyrite (a copper-iron sulfide) and tennantite-tetrahedrite (copper-arsenic sulfosalts) in rocks altered to quartz sericite-pyrite assemblages.

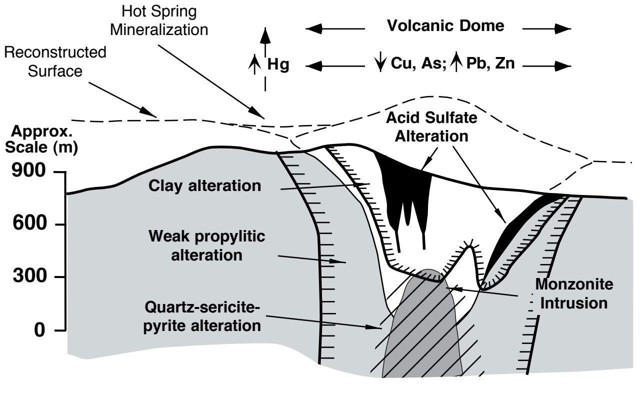

FIGURE 19.8—Generalized cross-section of a high-sulfidation deposit, based primarily on zoning relationships observed at Summitville, Colorado, and Julcani, Peru. Figure from Plumlee et al. (1995c), based on references contained therein.

Post-mineralization oxidation of these deposits typically occurs to great depths (more than 100 m deep at Summitville) along the permeable silica zones. This oxidation commonly removes the sulfides and concomitantly enriches the silica in gold. In contrast, the surrounding argillically altered rock is oxidized to very shallow depths (only several meters at Summitville), due to the low permeability created by the clay minerals.

Other deposit types that are commonly spatially and temporally associated with high sulfidation deposits include: porphyry Cu deposits, which form in the intrusive rocks at depth beneath the high sulfidation deposits; hot-spring Au/Hg deposits, which are the very near-surface manifestations of the high sulfidation system; and adularia-sericite epithermal deposits.

Drainage-water compositions

Intense acid leaching of the deposit host rocks, coupled with the high acid-generating potential of the sulfide minerals, are a geologic formula for extremely acidic and metal-bearing mine-drainage waters (Appendix, Fig. 19.9). The data compiled here were primarily collected as part of our ongoing geoenvironmental studies at Summitville, Colorado (Plumlee et al., 1995a, b; Plumlee and Edelmann, 1995). However, as part of this study, we have also collected limited data on mine waters from Red Mountain Pass, Colorado, and the 3R Mine, SE Arizona. We have also included here data on natural spring compositions draining unmined high sulfidation deposits at Mount Macintosh/Pemberton Hills, Vancouver Island, British Columbia, Canada (collected by Koyanagi and Panteleyev, 1993).

The most acidic and metalliferous waters are mine waters draining the acid-sulfate alteration portions of the deposits (Figs. 19.9, 19.10), due to the prior removal of nearly all buffering capacity of the rocks during intense, pre-ore, acid-sulfate alteration. Natural waters draining the acid-sulfate-altered portions of the unmined Mount Macintosh deposit (open circles on Fig. 19.9) have the same general range in pH as the mine-drainage waters, but have lower concentrations of Fe, Al, Cu, Zn, As, and other metals. This may reflect the lack of exposure of the base metal sulfides at the ground surface, a lower content of base metal sulfides, or lower permeability in the Mount Macintosh deposit.

Waters draining propylitically altered rocks at Summitville (triangular symbols, Fig. 19.9) have considerably higher pH values and correspondingly lower metal contents than those draining the acid-sulfate alteration zones. This is due to the presence of calcite in the propylitic alteration assemblage, which consumes acid generated by sulfide oxidation,

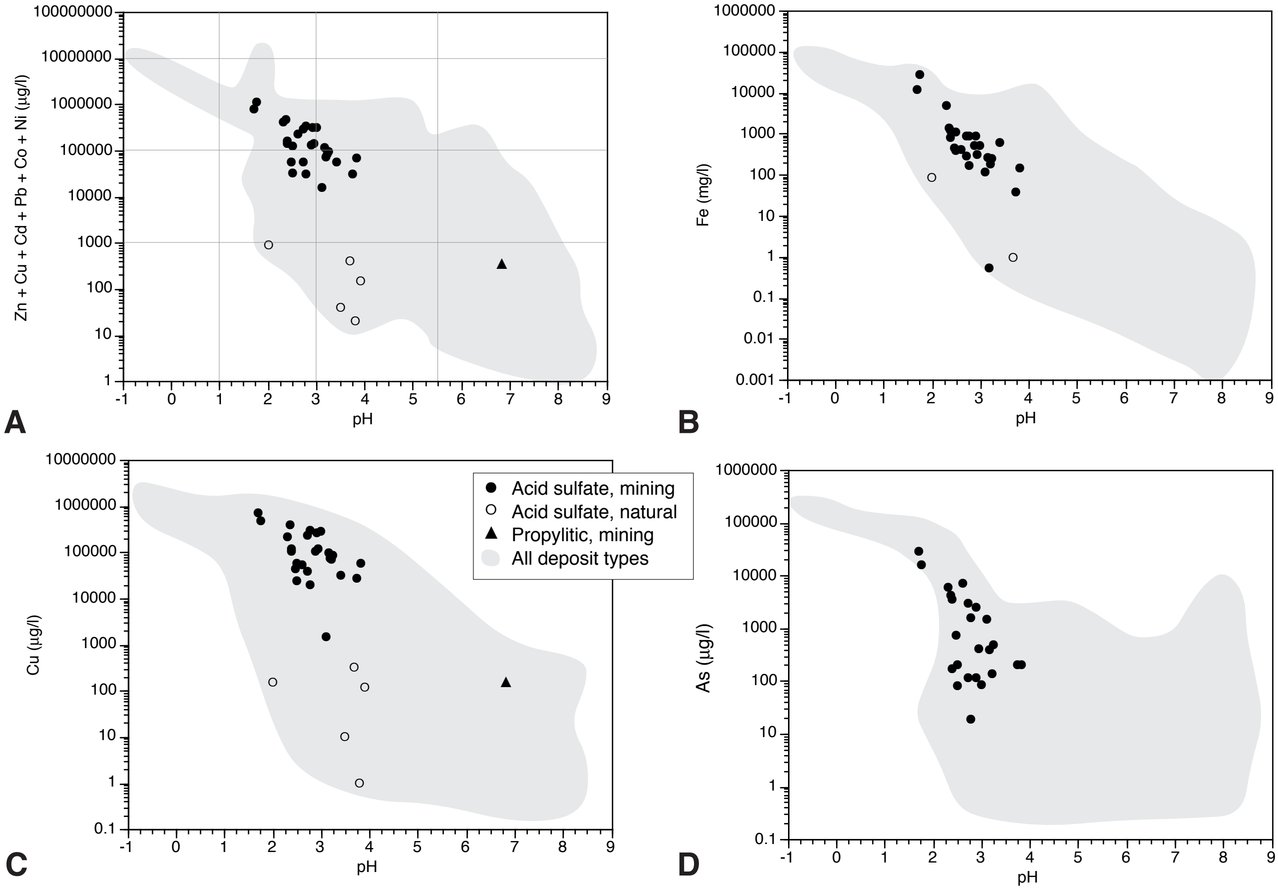

FIGURE 19.9—Plots of mine- and natural-drainage compositions for high sulfidation epithermal deposits: A. Ficklin diagram; B. Iron; C. Copper. D. Arsenic. Note differences in scale of the concentration axis between the plots. Shaded areas enclose all data points on corresponding Figures 19.1,

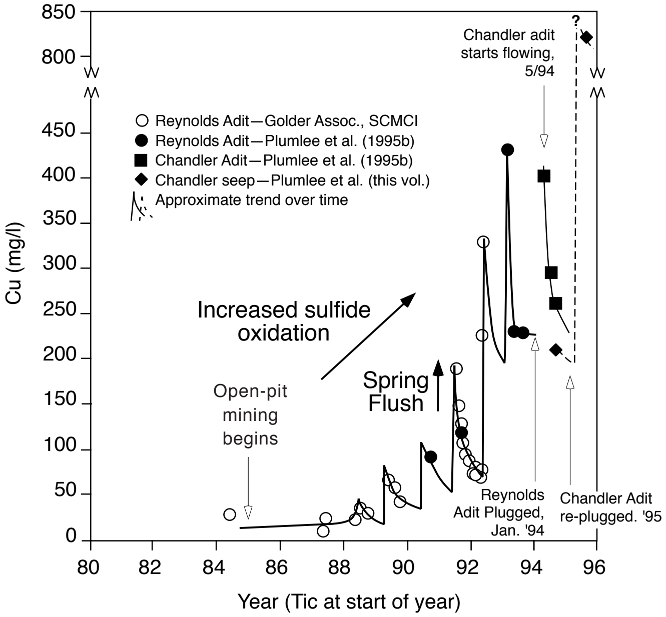

FIGURE 19.10—Plot of copper concentrations in adit outflows from the area beneath the Summitville open pit since the start of open-pit mining in 1985. The general increase in copper content over time reflects the increased exposure of sulfides as a result of mining, whereas the spikes in concentration each spring represent the flush of soluble salts from the mine workings during spring snowmelt. Figure from Plumlee et al. (1995b). The hollow symbols show data collected by Golder and Associates for the mining company, Summitville Consolidated Mining Co., Inc. (SCMCI on figure) prior to the bankruptcy of the company in 1992.

The mine waters draining high sulfidation deposits are generally enriched in copper relative to zinc and are relatively enriched in arsenic, due to the abundance of Cu-sulfides and Cu-As sulfosalts such as enargite in the deposits. Due to their highly acid pH, the waters also react readily with the surrounding wallrocks, and so can contain very high concentrations (Appendix) of a variety of elements leached from the wallrocks and ore minerals such as aluminum (several thousands of mg/l), rare earth elements (from several to tens of mg/l each of cerium, lanthanum, etc.), and cobalt, nickel, chromium, uranium, thorium, and beryllium (hundreds of µg/l up to several mg/l).

Soluble metal sulfate salts also play a key role in the generation of acid-mine drainage at Summitville and other high sulfidation deposits. Plots of copper concentrations in waters draining Summitville's Reynolds and Chandler adits over time since the beginning of open-pit mining show spikes in copper concentrations each spring, reflecting the snowmelt-triggered flush of soluble salts from the mine workings (Fig. 19.10). These adit waters are bright green, have a high ferrous iron content, and most likely reflect the dissolution of salts such as melanterite (a ferrous sulfate) and chalcanthite (a copper sulfate) from the mine workings. In addition, highly acidic, bright red puddles form within the open pit and on top of mine waste materials immediately after summer thundershowers, reflecting the dissolution of secondary salts. Evaporation of the acid waters during dry periods results in the re-precipitation of the salts, and, as a result, stores acid and metals until the next period of rain or snowmelt. Mineralogic studies of the salts in and around the Summitville open pit (Flohr et al., 1995) collected during dry season have identified a variety of salts, including chalcanthite and brochantite (Cu sulfates), jarosite (Fe-K hydroxysulfate), halotrichite (Fe-Al sulfate), and others.

Figure 19.11 is a Ficklin diagram comparing the compositions of the Summitville mine-drainage waters to those of waters derived by leaching of Summitville mine waste samples with deionized water, followed by evaporation of the leachate waters (Plumlee et al., 1995a). We interpreted the steep trend of metal content with pH shown by the leachate samples to reflect a short-term salt-dissolution trend. Evaporation of these samples led to shifts to lower pH and higher metal contents. The waters draining mine dumps, waters that collect in ponds during wet seasons, and adit waters collected during spring flush plot at the upper end of the salt dissolution trend. In contrast, adit waters collected during dry periods and waters from seeps outside the open pit area plot along a trend of shallower metal-pH slope, which merges at low pH with the salt dissolution trend. We interpreted this as a longer-term sulfide oxidation and water-rock interaction trend. Two low-volume seeps within the Summitville open pit, Blackstrap and Son-of-Blackstrap (Appendix) are the most acidic and metalliferous of all the drainage waters at Summitville; we interpreted these waters to result from the extreme evaporation of seep water that was ultimately derived from oxidation of sulfides and dissolution of secondary salts in the rocks around the open-pit.

Porphyry Cu and Cu-Mo deposits

Porphyry Cu and Cu-Mo deposits are large deposits characterized by disseminated to veinlet-controlled mineralization deposited throughout large volumes of altered, intermediate-composition intrusive rocks (see geologic summaries by Cox, 1986; Cox and

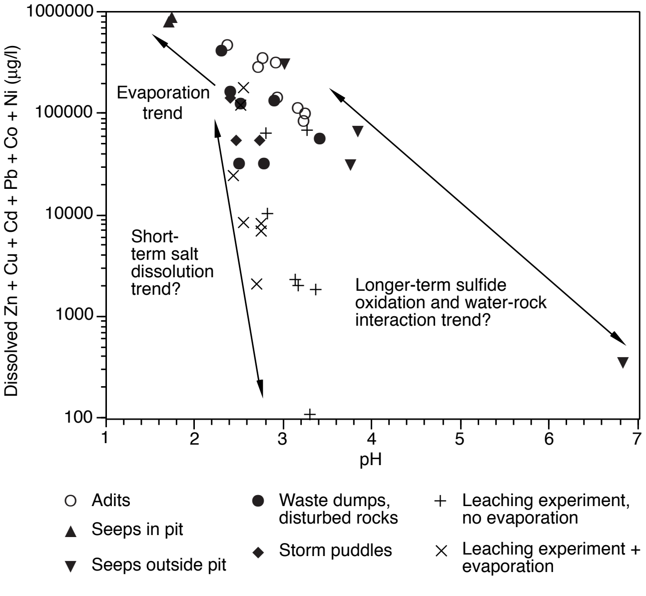

FIGURE 19.11—Ficklin diagram comparing mine-drainage compositions from Summitville, Colorado, with compositions of waters collected from leach studies using mine wastes from Summitville (Figure modified from Plumlee et al., 1995b).

Singer, 1986; Sillitoe, 1993; Cox et al., 1995; and references therein). The deposits formed from magmatic-hydrothermal fluids that were expelled during the crystallization of magmatic intrusions. A schematic cross section of a porphyry copper deposit showing distribution of mineralogic zones and wallrock alteration types (modified from Lowell and Guilbert, 1970) is shown in Filipek et al. (1999). The deposits are characterized by a central core of potassic alteration, where the intrusive rocks are altered to coarse potassium feldspar, biotite, and anhydrite. The core of potassically altered intrusive rocks is surrounded by a much broader phyllic alteration zone, where the intrusive rocks are altered to quartz-sericite-pyrite assemblages. The lateral fringes of the deposits are characterized by propylitic alteration of the rocks surrounding the intrusions to an assemblage containing epidote, chlorite, pyrite, and calcite. The upper portions of the deposits may be altered to clays, and in some deposits are overlain by advanced-argillic or acid-sulfate alteration with associated high-sulfidation or Cordilleran-lode deposits. Where the porphyry-forming magmas intruded into carbonate-bearing sedimentary host rocks, the disseminated and veinlet intrusive-hosted ores are mantled by skarn ores, where the sedimentary rocks as well as the outermost intrusive rocks are typically altered to calc-silicate, sulfide, and oxide mineral assemblages containing pyroxenes, garnets, wollastonite, epidote, magnetite, pyrite, chalcopyrite, and other sulfides.

Primary ore minerals that typically occur in porphyry-Cu deposits include pyrite, chalcopyrite, and variable but lesser amounts of bornite, enargite, and molybdenite. Porphyry molybdenum deposits contain molybdenite, lesser chalcopyrite, and typically do not contain enargite or bornite.

Post mineralization weathering of the deposits leads to a variety of minerals in the oxidized zone above the water table, including iron oxides (goethite, hematite, jarosite), copper oxides (such as tenorite and cuprite), and copper carbonates (malachite, azurite), copper silicates (chrysocolla, turquoise). During weathering, oxidized ground waters descend through the unsaturated portions of the deposits and leach copper, sulfur, iron, and other metals. When the descending waters reach the reducing conditions below the water table, the copper in the waters reacts with primary iron sulfides and chalcopyrite to produce supergene Cu-rich sulfide minerals such as chalcocite, covellite, bornite, digenite, djurleite, and others. In many porphyry deposits, significant copper grades occur in, and copper production comes from, these supergene enrichment ores.

Drainage-water compositions

The mine-drainage data that we have compiled from the literature (Appendix; Fig. 19.12) are from Globe, Arizona (Eychaner, 1988), and Mt. Washington, British Columbia (Kwong, 1991), and natural drainage data (open circles) are from the Alamosa River stock, a sub-economic Mo±Cu deposit south of Summitville, Colorado (Barry, 1996). Data for stream waters draining unmined porphyry-Cu deposits in Puerto Rico are summarized by Miller et al. (1982) and shown on Figure 19.12, but are not included in the Appendix.

Mine waters that drain the core potassic and quartz-sericite-pyrite alteration zones of porphyry copper deposits are quite acidic, with pH values as low as 2–3, and metalliferous, with total base metals from several mg/l to hundreds of mg/l (Fig. 19.12). As with the high-sulfidation epithermal and Cordilleran lode deposits, the copper-rich porphyry Cu deposits produce waters with Cu>Zn. Porphyry Mo deposits, on the other hand, tend to produce waters with relatively low base metal contents due to the generally lower abundances of base metal sulfides such as chalcopyrite and sphalerite. The natural drainage waters from the Alamosa River stock area (Barry, 1996) shown on Figure 19.12 have lower Cu and Zn concentrations because the mineralization is relatively Mo-rich, and Cu- and Zn-poor. Natural drainage waters collected from springs and streams within and near porphyry-Cu deposits

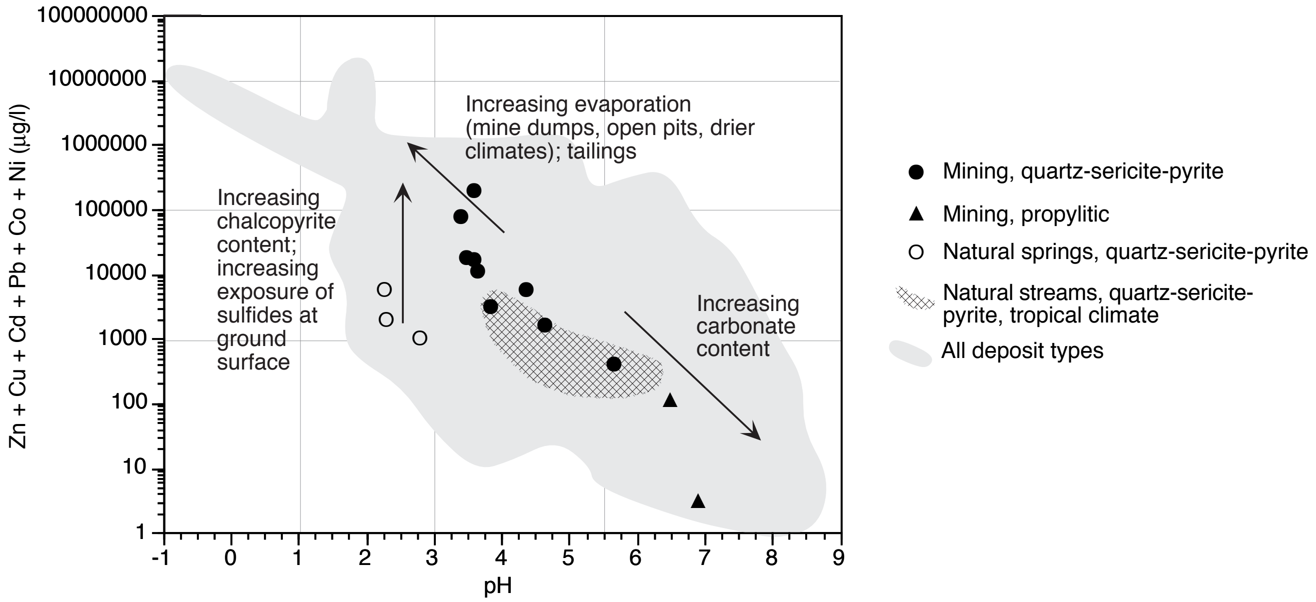

FIGURE 19.12—Ficklin Plot showing sum of dissolved base metals for mine- and natural-waters draining central quartz-sericite-pyrite and potassic alteration zones and peripheral propylitic alteration zones of porphyry Cu and Cu-Mo deposits. Shaded area encloses all data points on Figure 19.2.

in Puerto Rico (Miller et al., 1982) demonstrate that acidic (pH between 4 and 5) waters with elevated base metal concentrations (Cu as high as 4100 µg/l) can be produced, even in warm, wet, tropical climates where rainfall and dilution are substantial.

The role of drier climate in shifting drainage waters to somewhat lower pH values and higher dissolved metal concentrations can be seen by comparing the mine-drainage compositions (Appendix) from Globe, Arizona (Eychaner, 1988), with those from Mt. Washington, B.C. (Kwong, 1991) for similar alteration zones. The Globe waters are more acidic and metal-rich due to the drier climate of the Arizona desert versus the much wetter, cooler climate of British Columbia, shifts similar to those noted previously for VMS deposits.

Mine-drainage data from Mt. Washington (Kwong, 1991) also demonstrate the shifts to much higher pH values and lower metal contents in waters draining carbonate-bearing and (or) propylitically-altered rocks.

Cordilleran lode deposits

Cordilleran lode deposits (Bartos, 1987) are geologically similar to high sulfidation epithermal deposits, with the exception that they form at somewhat greater depths (4–5 km) in the Earth's crust. Instead of occurring within shallow volcanic centers, they form just above or in the upper levels of magmatic intrusions and their associated porphyry-copper deposits. Examples include Butte, Montana; Magma, Arizona; and Quiruvilca, Peru (Guilbert and Park, 1986; Bartos, 1987). These deposits are characterized by high contents of pyrite, enargite, chalcocite, covellite, bornite, and native sulfur. The sulfides occur in pipes or veins within wallrocks that were intensely altered prior to mineralization to advanced argillic assemblages containing kaolinite, pyrophyllite, ± alunite. The deposits are also typically zoned with increasing contents of sphalerite, galena, and carbonates (such as rhodochrosite) toward their peripheries. At Butte and other Cordilleran lode deposits, the high sulfidation veins and advanced argillic alteration crosscut earlier porphyry Cu or Mo mineralization; as a result, many economic geologists consider these deposits to be a variation of porphyry mineralization (Guilbert and Park, 1986). In addition, similar high-sulfidation mineralization may occur as a component of some polymetallic vein and replacement deposits associated with igneous intrusions into carbonate-rich sedimentary rocks (Morris, 1986).

Drainage-water compositions

The mine and natural waters draining Cordilleran lode deposits are likely to have compositions generally similar to those draining high sulfidation epithermal deposits, such as Summitville, with highly acidic, metal-rich waters having enrichments of copper relative to zinc, and enrichments of arsenic relative to other deposits with lesser amounts of arsenic-bearing sulfides. Limited water data are available for the open pit lake at Butte, Montana (Davis and Ashenberg, 1989) (Fig. 19.13). Because the "Main-stage" cordilleran lode deposits at Butte overprint an earlier porphyry Cu-Mo system, the mine waters are probably compositional hybrids reflecting both the lode veins and advanced-argillic alteration in the core of the deposit, and the earlier porphyry mineralization (see above for porphyry Cu/Mo water compositions); hence, their arsenic contents are somewhat elevated, but are lower than those of the waters draining Summitville. The Butte waters are among the most metal-rich of mine waters having similar pH values, in spite of the relatively wet climate; these enrichments presumably reflect evaporative concentration of the open-pit waters during dry periods. Although no drainage data are available for deposits on the carbonate-rich fringes of Cordilleran lode systems, it is likely that the pH values of waters draining the fringes are substantially higher, and metal contents are lower (with higher Zn/Cu) than those of waters draining the cores of the deposits.

Climax-type porphyry Mo deposits

Climax-type porphyry Mo deposits are geologically similar to the porphyry Mo deposits discussed previously, with the exception that they are genetically related to magmas enriched in silica, fluorine, and elements such as uranium and thorium (White et al., 1981). As a result, the deposits are hosted by silica- and uranium-rich granitic or rhyolitic intrusions, have abundant fluorite, and contain fluorine-rich alteration assemblages. The main orebodies consist of stockwork veinlets of quartz and molybdenite with lesser amounts of fluorite and pyrite. Late-stage fluorite (± manganiferous carbonate) veins also cross-cut the orebodies. The central portions of the deposits are generally lacking in base metal sulfides such as chalcopyrite, sphalerite, and galena; however, sphalerite and galena increase in abundance, along with calcite and rhodochrosite, toward the lateral fringes of the deposits. The wallrocks hosting the deposit are altered to the same potassic (cores of the deposits), phyllic (intermediate portions), argillic (upper levels), and propylitic (lateral edges of the deposits) assemblages seen in porphyry Cu and Cu-Mo deposits. In addition, in the deeper levels of the deposits, the wallrocks are altered to so-called "greisen" assemblages containing quartz, topaz, and muscovite (White et al., 1981). Garnet is a common alteration mineral in some portions of the deposits. Examples of Climax-type deposits include Climax, Henderson, and Mt. Emmons, Colorado (White et al., 1981).

Drainage-water compositions

Limited mine-drainage data collected as part of this study from Climax, Colorado (Appendix, Fig. 19.14), show that waters draining mine waste material from the potassic and phyllic alteration zones can be highly acidic (pH < 2). The rates at which feldspars, sericite, and biotite weather are apparently sufficiently slow compared to rates of sulfide oxidation that they do not readily neutralize acid generated by sulfide oxidation. Due to the general lack of Cu, Zn, and Pb sulfides in the potassic and phyllic alteration zones, the mine waters may have slightly lower dissolved concentrations of Cu, Zn, and Pb than waters of equivalent acid pH values that drain other deposit types (Fig. 19.14). Due to the abundance of fluorine in the ores, wallrock alteration, and host rocks, the mine waters are exceptionally enriched in fluoride, with concentrations as high as 710 mg/l (Appendix). As a result of the uranium enrichments in the deposit host rocks, coupled with the low pH and high fluoride concentrations (uranyl fluoride complexes are very stable), the mine waters from Climax also have among the highest levels of dissolved uranium (8–9 mg/l; Fig. 19.14B) of mine waters we have measured in this study or noted in the literature. The acidic waters from Climax also have the highest molybdenum concentra-

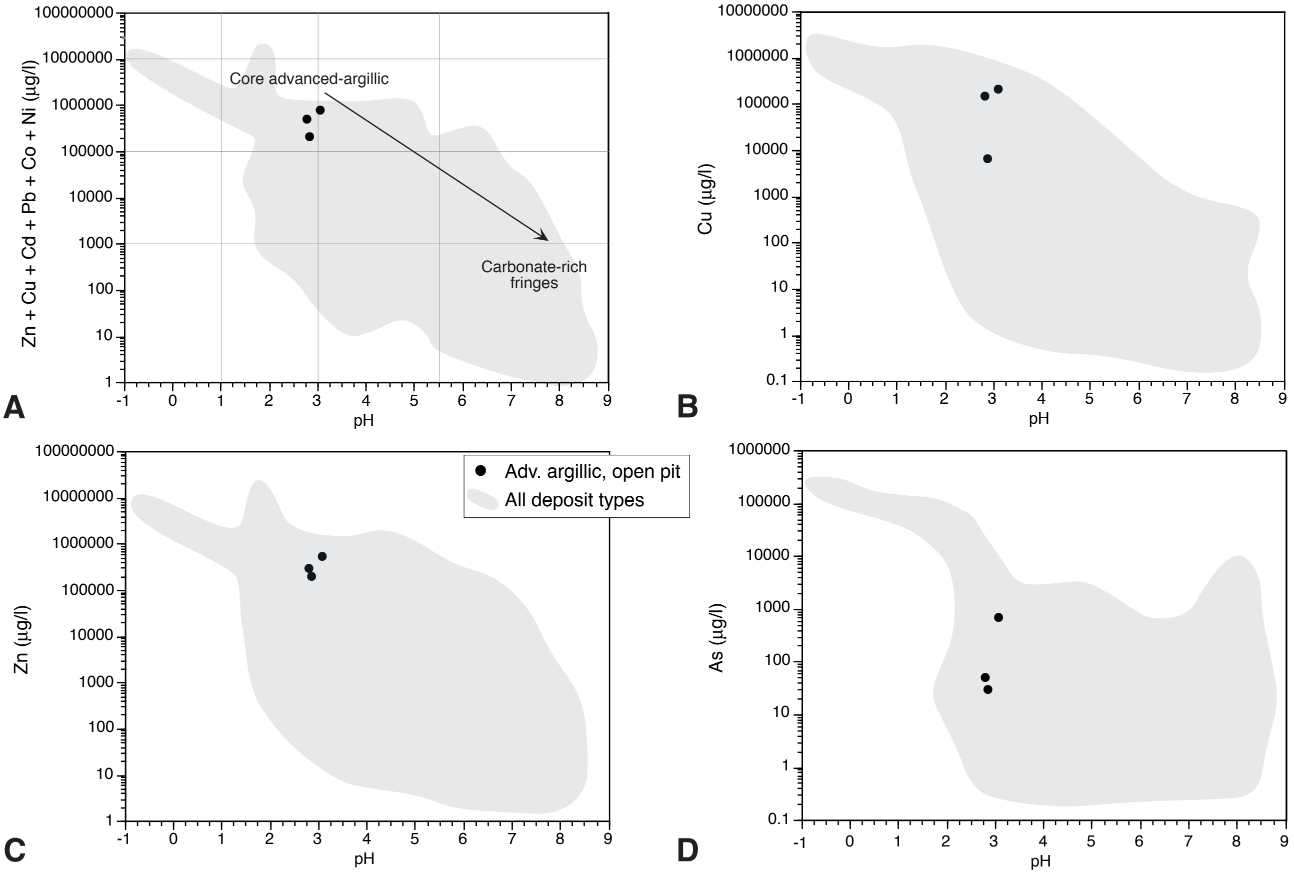

FIGURE 19.13—Plots of open-pit water compositions at Butte, Montana. The deposits at Butte include Cordilleran lodes (veins) superimposed on earlier porphyry-Cu-Mo mineralization: A. Ficklin diagram; B. Copper; C. Zinc; D. Arsenic. Note differences in scale of the concentration axis between the plots. Shaded areas enclose all data points on corresponding Figures 19.1, 19.2.

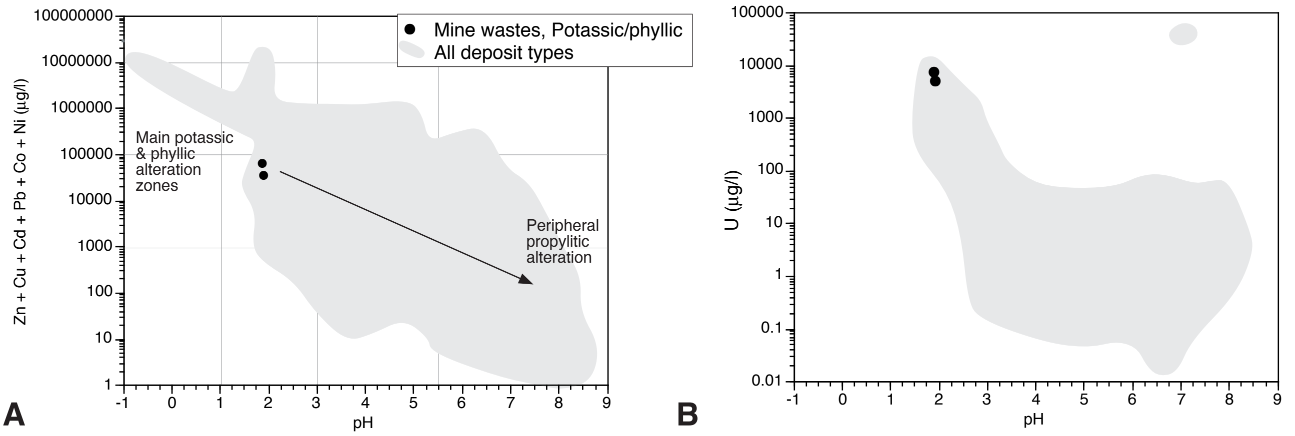

FIGURE 19.14—Plots of mine-drainage compositions for waters draining the central quartz-sericite-pyrite and potassic alteration zones of Climax-type porphyry Mo deposits. A. Ficklin diagram; B. Dissolved uranium. Note differences in scale of the concentration axis between the plots. Shaded areas enclose all data points on corresponding Figures 19.1, 19.2.

tions (several hundred µg/l) among acid-mine water compositions we have measured in this study; however, these concentrations are substantially lower than those measured in alkaline mine waters (up to 42 mg/l) draining sandstone uranium deposits from the southwestern U.S. (Appendix; Longsworth, 1994). The mine waters at Climax are currently being treated to neutralize acid and precipitate metals.

Polymetallic vein deposits and adularia-sericite epithermal vein deposits

We have discussed in previous sections deposit types in which the predominant ore zones or ore types are likely to produce acidic, metal-bearing waters. We will now discuss deposit types with major ore zones or ore types that can produce waters with variable pH but generally high levels of dissolved metals.

Polymetallic vein systems and adularia-sericite epithermal vein deposits are deposited from convectively circulating meteoric hydrothermal systems similar to the present-day geothermal systems at Yellowstone, USA, and the North Island of New Zealand (Berger and Eimon, 1983; Heald et al., 1987; Sillitoe, 1993). The deposits are often genetically and spatially related to igneous intrusions at depth, which provide the heat source for the hydrothermal systems, and possibly also fluids, gases, metals, and other constituents carried upward by the fluids and incorporated into the ores. The epithermal deposits form in the upper 1–2 km of the crust, and are characterized by veins, stockwork veins, and mineralized breccias in mostly volcanic host rocks. Polymetallic vein deposits form at slightly greater depths (several km) than epithermal veins, and typically are composed of veins and stockworks hosted by a variety of rock types such as granites and metamorphic rocks.

Both types of deposits can be quite variable and complex from a mineralogical standpoint, depending upon the compositions of the hydrothermal fluids which formed the deposits, the ore deposition mechanism(s), the wallrocks, and the chemical evolution of the hydrothermal fluids during mineralization. Both types of deposits can also show very strong spatial variations in mineralogy within an ore shoot, within a vein or vein system, and across entire districts.

Polymetallic vein deposits (such as Central City, Colorado; Sims et al., 1963) are often characterized by large-scale, district-wide zoning patterns. Mineralogically, they are relatively similar to the Cordilleran lode deposits discussed earlier, with the exception that they do not have the well-developed advanced-argillic alteration assemblages typical of the central portions of the Cordilleran lode deposits. The central portions of polymetallic districts (which form closest to the igneous heat source) are typically Au-rich and characterized by a relatively simple assemblage of quartz and pyrite, with lesser chalcopyrite, galena, and sphalerite (± enargite, arsenopyrite). Sphalerite, galena, and carbonates such as rhodochrosite and calcite increase in abundance, toward the outer portions of the districts. Quartz-sericite-pyrite alteration of the wallrocks is common in the central portions of the districts, whereas propylitic alteration of the wallrocks to carbonate, epidote, chlorite, and pyrite is most abundant on the fringes of the district.

The adularia-sericite epithermal deposits (examples include Creede and Bonanza, Colorado; Comstock, Nevada; and Sado, Japan) are so-named due to the abundance of these minerals as vein fill and alteration minerals (Berger and Eimon, 1983; Heald et al., 1987; Sillitoe, 1993); however several different subtypes have been identified, including Creede-, Comstock-, and Sado-type (all named after their characteristic mining districts). All are characterized by simple sulfides (such as sphalerite, galena, and chalcopyrite), sulfosalts (sulfides containing significant As, Sb, ± Bi), gold, electrum, silver, ± tellurides as important ore minerals. Quartz, carbonates, and adularia (± barite, chalcedony, and fluorite) are important gangue minerals. Creede-type veins are typically silver-rich, and are dominated by pyrite, sphalerite, galena, and chalcopyrite, with variable but lesser amounts of carbonates, quartz, and barite. Comstock-type veins are typically gold-rich, and are dominated by quartz and adularia, ± carbonates, with pyrite, sphalerite, galena, and other sulfides comprising less than several percent of the vein material. Sado-type veins are Cu-rich equivalents of Comstock-type veins, with quartz, adularia, and carbonates predominating over chalcopyrite. Strong lateral and vertical variations in vein mineralogy may be present in all three epithermal deposit types, and are especially common in the Creede type. An example of mineral zoning along one vein in the Bulldog Mountain Mine at Creede is shown in Plumlee (1999). Strong lateral and vertical variations in wallrock alteration assemblages (silicification, propylitic, argillic, advanced argillic) are also typical in all three epithermal vein deposit types, with intense silicification, and pervasive argillic and advanced argillic alteration common adjacent to shallow portions of the veins, moderate silicification (± potassic alteration) close to veins in the deeper levels, and propylitic alteration away from the veins.

Drainage-water compositions

Both polymetallic vein and adularia-sericite epithermal vein deposits can exhibit a wide spectrum of mine- and natural drainage compositions (Appendix, Figs. 19.15 and 19.16), depending upon the base-metal sulfide and pyrite content of the veins, the carbonate content of the veins and wallrock alteration, and the extent of interaction between the drainage waters and the carbonates. Mine and natural waters for polymetallic vein deposits include those collected as part of this study from the Central City and other districts in Colorado, and those collected by Smith (1991) from the St. Kevins Gulch district, Colorado. Waters draining adularia-sericite epithermal deposits include those collected as part of this study from the Creede, Bonanza, and Silverton, Colorado, districts; the Appendix also includes data collected by Moran (1974) from Bonanza, Colorado. The drainage data listed in the Appendix are primarily from the Rocky Mountains of Colorado, but also include two samples collected from the World's Fair district in Arizona. Price et al. (1995) summarize mine water data from several polymetallic vein deposits and adularia-sericite epithermal vein deposits in Nevada.

In general, the most acidic, metal-rich underground mine waters are those that drain pyrite- and base-metal-sulfide-rich ores in sericitically altered igneous rocks, carbonate-poor metamorphic rocks, or highly welded volcanic rocks (polymetallic—Druid, Idaho, and St. Kevins Gulch, Colorado; epithermal—Solomon and Alpha Corsair, Creede district, Colorado). Deposits that are pyrite-rich but that contain significant carbonate minerals in their gangue or wallrock alteration (such as the American Tunnel, Silverton, Colorado) tend to have mine waters with near-neutral pH values but elevated levels of dissolved zinc (as high as many tens of mg/l) and copper (as high as several mg/l). As discussed previously the elevated dissolved zinc levels reflect zinc's tendency to not

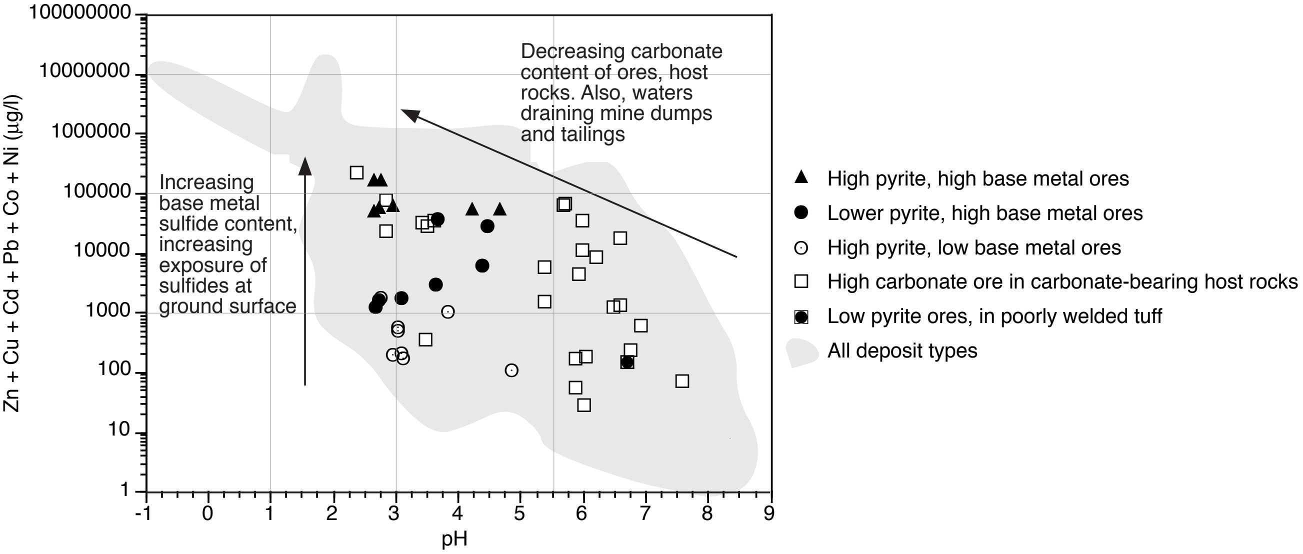

FIGURE 19.15—Ficklin plot showing the dissolved sum of base metals in mine and natural waters draining polymetallic vein and adularia-sericite epithermal vein deposits. Due to general similarities in the geologic characteristics of the deposits, the waters are not grouped according to deposit type. Shaded area encloses all data points on Figure 19.2.

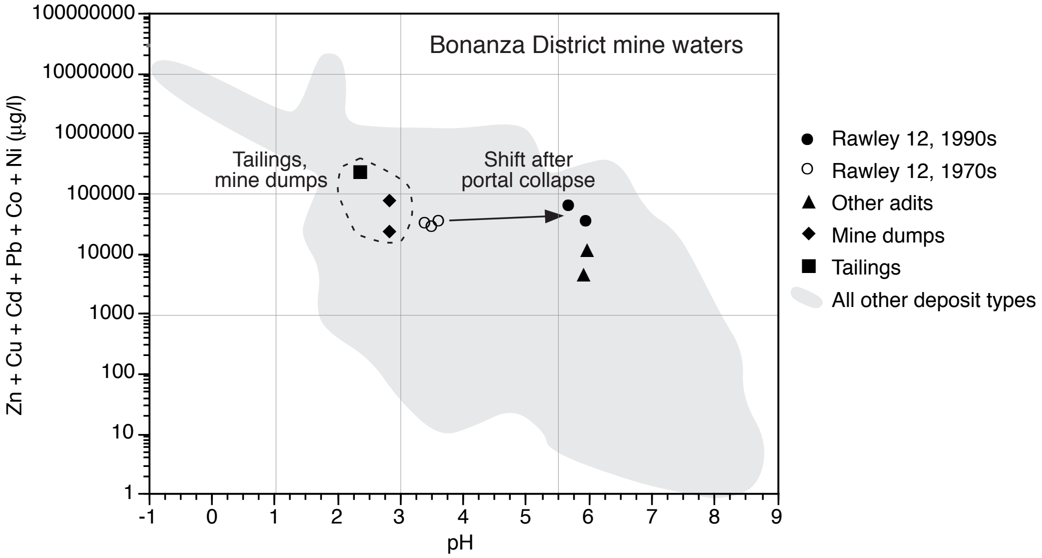

FIGURE 19.16—Ficklin plot showing the dissolved sum of base metals in mine waters draining adularia-sericite epithermal vein deposits in the Bonanza district, Colorado. The veins contain abundant pyrite, sphalerite, galena, and chalcopyrite, and very little carbonate. The volcanic host rocks, however, are variably propylitized to contain carbonate. See text for explanation of different water compositions. Shaded area encloses all data points on Figure 19.2.

sorb onto particulates at near-neutral pH values, and the elevated dissolved copper levels reflect copper's tendency to desorb from particulates due to competition from copper carbonate complexes (Smith, 1999). If oxygenated, the near-neutral waters can also carry substantial amounts of zinc, lead, copper, and other metals in suspended hydrous ferric oxide particulates.

Compositions of waters draining underground mine workings in the Central City district, Colorado, illustrate the substantial variations in composition that can occur across a district as a result of large-scale zoning of the vein mineral assemblages. As initially pointed out by Wildeman et al. (1974), waters draining quartz-pyrite veins in the central portions of the district (see Druid seep and Idaho adit water compositions in Appendix) are highly acidic and metal-rich. In contrast, increasing carbonate content and decreasing pyrite content of the veins toward the lateral portions of the district results in mine waters that have progressively higher pH and lower base metal contents (e.g., the National Tunnel water compositions in the Appendix). Plumlee (1999) includes figures showing both the Central City district mineral zoning patterns and variations in mine-water composition across the district.

As demonstrated by mine, waste, and tailings waters in the Bonanza district, Colorado (Fig. 19.16), substantial ranges in drainage pH and metal content can occur in a given deposit where pyrite-rich, carbonate-poor veins are hosted by propylitically altered wallrock (Fig. 19.16). Waters flowing primarily along the veins are typically quite acidic and metal-bearing, because they interact little with the carbonate minerals in the wallrock alteration. If fracture systems or mine workings route the waters through the altered rock, or if the acidic waters from the veins mix with waters from unmineralized fractures in the altered wallrock, then higher pH values result. Highly acidic waters may occur in tailings due to the selective concentration of pyrite by depositional winnowing within the tailings impoundments. Mine dump waters may also be acidic if the dumps have large amounts of pyritic vein or wallrock materials. Dissolution of soluble salts in the dumps by storm or snowmelt waters can may generate acid that is not buffered due to lack of time or opportunity to react with carbonate minerals in the dumps.

Compositional shifts of the waters draining the Rawley adit, Bonanza, Colorado, from the 1970s (Moran, 1974) to the 1990s (this study) illustrate the complex interactions between hydrology, geology, and geochemistry that can take place in pyritic veins hosted by propylitically altered wallrock (see data in Appendix and Fig. 19.16). In the early 1970s, the adit was open to at least 700 m in from its portal (R. Moran, oral commun., 1995). At some point during the mid to late 1970s, the portal collapsed, leaving only a small, several-cm opening at the top of the portal from which the waters flowed. In 1973 and 1974, the adit waters were quite acidic (pH 3.7) (Moran, 1974). The adit waters we measured in this study in 1992 and 1993 had much higher pH (around 6) and very low dissolved oxygen. The dissolved concentrations of the predominant metals (Fe, Al, Zn, Cu, Pb) are substantially greater in the higher-pH 1990s waters than in the more acidic 1970s waters. Our interpretation of these compositional shifts is that the ponding of the waters behind the collapsed portal (1) allowed the waters to interact more with the propylitically altered wallrock (thereby helping to maintain a near-neutral pH), and (2) allowed the waters to remain unoxygenated until they flowed out the portal opening (presumably, this inhibited the formation of hydrous ferric oxide particulates, a resulting drop in pH, and sorption of metals onto the particulates).

Hot-spring Au-Ag and Hg deposits

Hot spring deposits form where hydrothermal systems flow near to, and (or) discharge onto the Earth's surface; they are commonly associated with epithermal vein deposits at depth, as both may form from the same meteoric-hydrothermal systems. Two dominant types are noted, depending upon the dominant metal of value: hot-spring Au-Ag (Berger, 1986), and hot-spring Hg (Rytuba, 1986). Both types of hot spring deposits are enriched in the suite of trace elements commonly referred to as "mobile epithermal," which includes As, Sb, Hg, Tl, and Au. The deposits consist of chalcedony- and opal-bearing sinter terraces that formed where hydrothermal fluids discharged onto the Earth's surface. The deposits are underlain by stockwork vein systems that contain silica minerals (quartz, chalcedony, opal), adularia, carbonates (such as calcite), sulfides (including pyrite, marcasite, stibnite, realgar, cinnabar), ± native sulfur, ± native mercury. Ore deposition resulted from boiling and cooling of the hydrothermal fluids, and mixing of the hydrothermal fluids with shallow ground waters. Near-surface condensation and oxidation of H_2S boiled from the hydrothermal fluids produces shallow acid-sulfate alteration of the wallrock to alunite, kaolinite, and clays. With increasing depth, the rocks are variably silicified and altered to contain adularia, carbonates, and chlorite. Examples of hot spring deposits include Leviathan, Sulphur Bank, and McLaughlin, California, and Round Mountain, Nevada (Tingley and Bonham, 1986).

Drainage-water compositions

Selected mine drainage data exist. Those available are from the hot-spring deposit at the Leviathan mine, California, (Ball and Nordstrom, 1989) are included in the Appendix and shown on Figure 19.17. The Leviathan waters are highly acidic, and drain wallrocks that have been altered to an acid sulfate assemblage containing alunite, kaolinite, clays, native sulfur, pyrite, marcasite, and chalcopyrite. Due to the general lack of base metal sulfides in the ores, the Leviathan mine waters have a lower sum of base metal concentrations than most other highly acidic mine waters. As a result of the presence of chalcopyrite in the ores and the lack of sphalerite, dissolved copper levels exceed those of zinc. The waters also contain relatively high concentrations of dissolved Co, Ni, and Cr (1–14 mg/l), which may have ultimately been derived from the host andesite volcanics. The arsenic-rich nature of the ores is manifested in the arsenic-rich mine water compositions, which are exceptionally enriched in arsenic and have the highest arsenic concentrations (as high as 45 mg/l) of all similarly acidic waters draining all deposit types. Thallium concentrations are also exceptionally high (near 1 mg/l; Ball and Nordstrom, 1989), again reflecting the enrichments of this "mobile epithermal" element in this type of deposit.

The Leviathan data reflect waters draining the most acid-generating portions of hot spring deposits. We have not sampled or seen data in the literature for mine waters draining stockwork ores, although a broad range in possible pH values and metal contents is possible given the mineralogy of the stockwork ores. If carbonate minerals are abundant, as at McLaughlin, California, it can be inferred (based on analogies with other deposits containing arsenic sulfides and carbonates for which drainage data are available) that drainage waters may have near-neutral pH values and somewhat elevated concentrations of arsenic (as high as several hundred µg/l?). In stockwork ores with lower carbonate mineral contents and high contents of pyrite and marcasite, it is possible that the drainage waters could be more acidic, with correspondingly higher concentrations of arsenic. Dissolved animony concentrations could also be elevated, especially in acidic waters.

The data available from the literature do not include analyses for mercury. However, unpublished drainage data recently collected by J. Rytuba for several mercury deposit types indicate that the greatest concentrations of Hg in drainage waters arise due to the dissolution of soluble Hg salts from wastes left over after the roast-processing of the ores (J. Rytuba, oral commun., 1997). Concentrations of mercury in the most acid waters may reach as high as several mg/l Hg total, and several hundred µg/l methyl mercury, its most toxic form (J. Rytuba, oral commun., 1997).

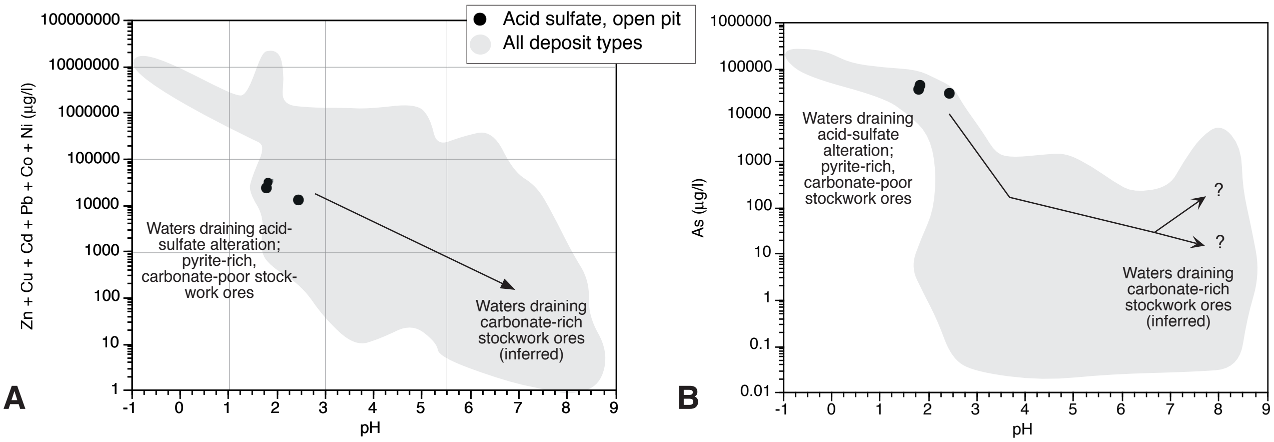

FIGURE 19.17—Plots of mine-drainage compositions for waters draining quartz alunite alteration in the Leviathan, California, hot spring deposit. A. Ficklin diagram; B. Dissolved arsenic. Note differences in scale of the concentration axis between the plots. Shaded areas enclose all data points on corresponding Figures 19.1, 19.2.

Skarn and polymetallic replacement deposits

Skarn and polymetallic replacement deposits are genetically related to magmas that intrude into sedimentary rock sequences; they form when magmatic-hydrothermal fluids are expelled from the magmas and react chemically with the sedimentary rocks. Both types of deposits may therefore be spatially associated with and genetically related to porphyry-Cu, -Cu-Mo, or -Climax-Mo deposits (Fig. 19.18). Examples of polymetallic replacement deposits include: Leadville, Gilman, and Rico, Colorado: New World, Montana; and Park City and Tintic, Utah. Skarn ores are relatively minor ore types in districts with major replacement deposits; however, the New World district does have important skarn and replacement ores. There are skarn deposits associated with a number of porphyry-Mo, -Cu-Mo, and -Cu deposits worldwide, such as Yerington, Nevada; Chino district, New Mexico (the Groundhog deposit), and others.

Skarn deposits typically occur on the outermost portions of their associated intrusions (endoskarn) or in the sediments adjacent to the intrusions (exoskarn) (Hammarstrom et al., 1995). Both the sedimentary and igneous host rocks are intensely altered to a mineral assemblage dominated by carbonate minerals and calc-silicate minerals such as diopside-hedenbergite, wollastonite, tremolite-actinolite, and garnets. Ore minerals in the skarns typically include chalcopyrite, sphalerite, and galena, and are commonly related to carbonate-rich alteration assemblages. Common iron minerals include pyrite, magnetite, and hematite. The skarn ores typically occur as veins, massive lenses, or disseminations within the calc-silicate-altered host rocks.

Polymetallic replacement deposits may be Pb-Zn-rich or Cu- (± Au-) rich. In general, the replacement deposits that are deeper and proximal to the the intrusive stock are Cu-rich, with increasing Pb and Zn and decreasing Cu with increasing distance from the stock (Morris, 1986; Titley, 1993). In addition, polymetallic replacement deposits that are associated with porphyry-Mo deposits have higher Pb and Zn than those that are associated with porphyry-Cu deposits. Several different ore types are typical of the polymetallic deposits, and may include: massive sulfide lenses and veins occurring within and (or) replacing sedimentary host rocks; mineralized breccias within the sedimentary rocks, and; veins within associated igneous sills and dikes (Fig. 19.18). The deposits typically consist of Fe-rich sphalerite, galena, pyrite, marcasite, chalcopyrite, argentite, ± tetrahedrite, ± enargite, ±-digenite, and native Au (Morris, 1986; Titley, 1993). Chalcopyrite, enargite, and native gold are more abundant in replacement deposits that are proximal to the igneous intrusions. Quartz and carbonate minerals such as calcite also are present as gangue minerals. Some calc-silicate alteration of the sedimentary host rocks, as well as alteration of carbonate sedimentary rocks to jasperoid may also be present. The igneous host rocks are typically altered to quartz-sericite-pyrite assemblages.

Drainage-water compositions

We have collected mine-water samples from several polymetallic replacement districts in Colorado (Leadville; Bandora, near Silverton) and Utah (mines unidentified at property owner's request). We have also included in our database (Appendix) published mine-water compositions from polymetallic replacement deposits at Gilman, Colorado, and from polymetallic replacement and skarn deposits from New World, Montana (Pioneer Technical Services, 1994). The mine water compositions show a broad range in pH and metal content that can be ascribed to differences in ore types (Fig. 19.19).

Mine-waters draining the skarn deposits at New World are quite acidic and have relatively high levels of dissolved metals (Fig. 19.19). We interpret this to reflect the lack of neutralizing reactions between the acid waters and the calc-silicate alteration minerals in the skarns, and the lack of reactions with any carbonate minerals that may remain in the original sedimentary host rocks. The interpreted lack of reactivity of the calc-silicate skarn minerals is intriguing, given that these minerals have been noted to be more reactive than many of the rock-forming silicate minerals (Kwong, 1993). The copper-rich nature of the New World skarn ores is reflected in the higher levels of Cu relative to Zn in the waters.

In contrast to the acidic waters draining the New World skarn ores, Eppinger et al. (1997) found that spring waters draining Au-skarn ores of the Nabesna district, Alaska, have near-neutral

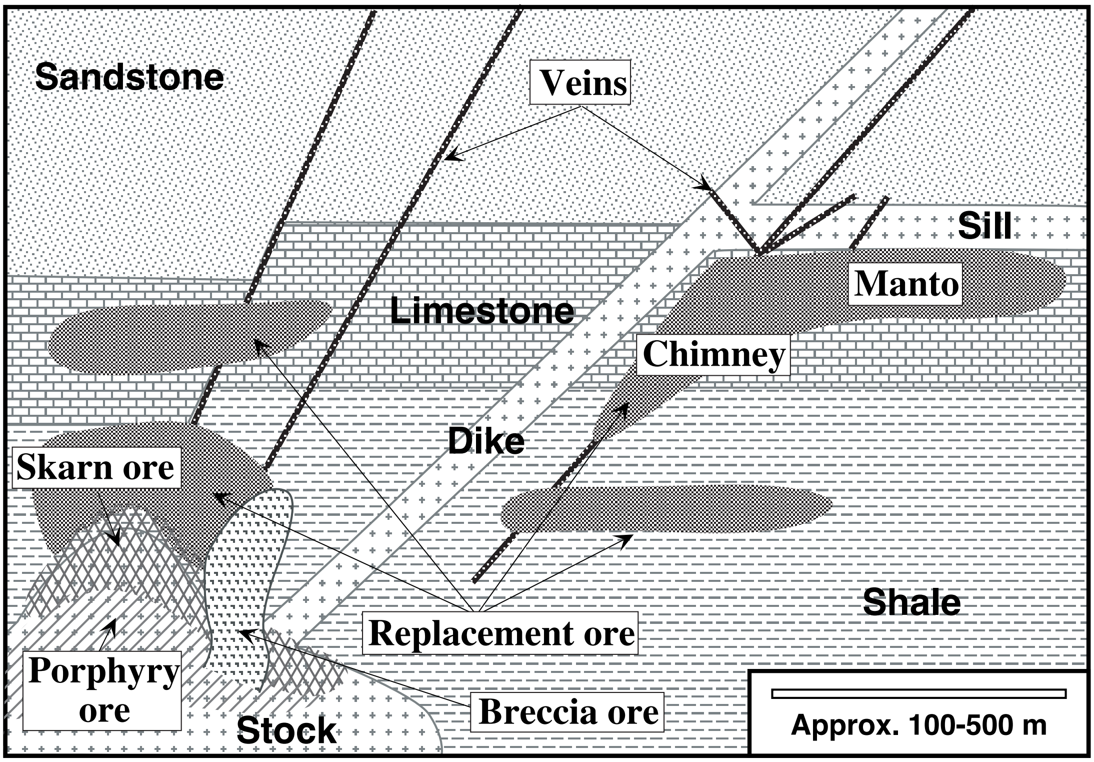

FIGURE 19.18—Conceptual cross section showing mineral-deposit types that are commonly associated with intrusions of magma into sedimentary rock sequences.

pH values with low dissolved metal concentrations (data are not included in the Appendix, but their compositional ranges are shown on Fig. 19.19). These differences presumably reflect a much greater proportion of acid-buffering carbonate minerals in the Nabesna deposit. However, leach studies of Nabesna tailings and mine waste samples collected during a dry period showed that quite acidic and metal-rich waters may form during rainfall or snow melt events due to the dissolution of soluble secondary salts in the tailings and mine waste materials (Eppinger et al., 1997).

Polymetallic replacement ores hosted by carbonate sedimentary rocks tend to have mine-drainage water compositions that are relatively near-neutral pH (due to the acid-buffering capacity of the host rocks), but that can carry quite high levels of zinc (as high as 170 mg/l) and some copper (as high as several mg/l in waters draining copper-rich orebodies). In general, the highest Zn and Cu concentrations (several mg/l to tens of mg/l Zn and up to several mg/l Cu) occur in waters that drain pyrite-rich ore bodies and that contain low dissolved oxygen; the low oxygen levels prevent hydrous ferric oxides from precipitating and then sorbing the Zn and Cu. Where the near-neutral waters are oxidized, the amount of iron precipitates that form are generally small, and therefore do not serve as a ready sorption sink for the Zn. We do not currently have drainage data for waters draining carbonate-rich mine waste piles and tailings from polymetallic replacement deposits. It is possible that storm or snow-melt waters draining mine wastes and tailings may be quite acidic and metal-bearing if acid generated by dissolution of acid-storing soluble salts does not react sufficiently with the carbonates, either because of rapid runoff rates from the wastes or the armoring of the carbonate rock surfaces by hydrous iron or aluminum oxides.

Mine waters draining polymetallic veins hosted by igneous dikes and sills, such as the Yak Tunnel waters (Appendix), are acidic and metal-rich (Fig. 19.19), due to the lack of acid-neutralizing capacity of the sericitically altered igneous host rocks, and are similar in composition to waters draining polymetallic veins in districts (such as Central City, Colorado) without carbonate rocks.

Stratiform shale-hosted (SEDEX) deposits

Shale-hosted massive sulfide deposits (also termed sedimentary-exhalative, or SEDEX) are characterized by massive beds of sulfides within black shale and chert-bearing host rocks (Large, 1980; Goodfellow et al., 1993; Kelley et al., 1995). These syngenetic deposits are similar in some respects to the volcanogenic massive sulfide deposits discussed earlier, in that they are thought to have formed through the discharge of hydrothermal fluids onto the sea floor, and are somewhat similar in ore mineralogy and texture. They are different from the VMS deposits, however, in their predominantly black shale and chert host rocks, lesser carbonate host rocks, and in their geologic occurrence in failed continental rifts. The deposits can be very extensive laterally, from hundreds of meters to kilometers (Kelley et al., 1995). Examples include: Red Dog, Lik, and Drenchwater, Alaska; Sullivan, British Columbia; and Mt. Isa and Broken Hill, Australia.

Strong primary mineral zoning is common in SEDEX deposits.

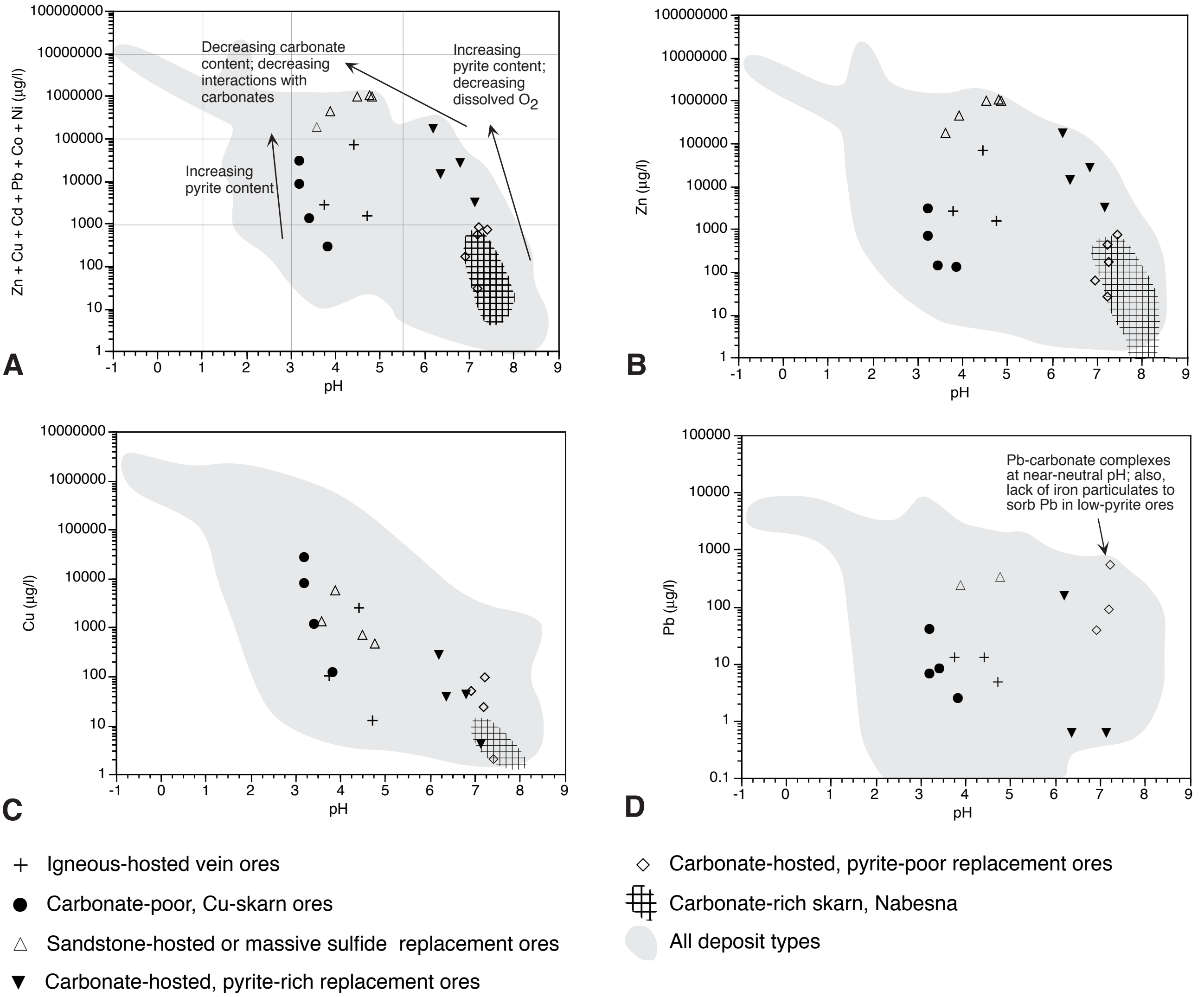

FIGURE 19.19—Plots of mine-drainage compositions for waters draining skarn and polymetallic vein and replacement deposits. A. Ficklin diagram; B. Dissolved Zn. C. Dissolved Cu. D. Dissolved Pb (Nabesna skarn waters had Pb concentrations below 0.1 µg.l). Note differences in scale of the concentration axis between the plots. Shaded areas enclose all data points on corresponding Figures 19.1, 19.2.

The feeder system for the hydrothermal fluids (which is generally linked to a syn-sedimentary fault) is characterized by high degrees of alteration of the host cherts and carbonates to quartz, muscovite, chlorite, siderite, ankerite, tourmaline, and lesser chalcopyrite, pyrrhotite, pyrite, galena, sphalerite, tetrahedrite, and arsenopyrite (Goodfellow et al., 1993). Overlying the feeder zone is the vent complex, where the hydrothermal fluids discharged onto the ocean floor. This is marked by massive, vein, and replacement sulfides such as pyrite, pyrrhotite, marcasite, galena, and sphalerite, with lesser chalcopyrite, arsenopyrite, and sulfosalts. Carbonates may also be in the vent complex. The vent complex mineralization grades laterally into bedded ore facies sediments, with hydrothermal mineral beds (containing pyrite, pyrrhotite, marcasite, sphalerite, galena, barite, calcite, witherite, siderite, and ankerite) interlayered with beds of the host cherts, shales, or carbonates. Distal sedimentary facies occur lateral to the bedded ore facies, and are marked by low-grade hydrothermal barite, ± pyrite, ± phosphatic chert beds interlayered with the host rock beds.

Sulfides in the bedded portions of the deposits are typically very fine grained (Goodfellow et al., 1993; Kelley et al., 1995). Framboidal and botryoidal textures in the sulfides are common. Crustiform textures and coarser grain sizes are more common in the feeder zones.

Other than the predominant Pb, Zn, and Cu, trace elements that are variably enriched in SEDEX deposits are cadmium (in sphalerite); silver, arsenic, and antimony (in sulfosalts and possibly in botryoidal pyrite/marcasite); and mercury (which can reach quite high levels in pyrite, sphalerite, and sulfosalts) (Kelley et al., 1995).

Drainage-water compositions

Although there are probably mine-drainage data available for SEDEX deposits, we have not yet encountered any in the literature. Several studies have examined natural pre-mining drainage signatures of SEDEX deposits in the Alaskan Brooks Range, and representative data from these studies are included in the Appendix and shown graphically on Figure 19.20.

Kelley and Taylor (1997) compared the compositions of natural stream waters draining several unmined SEDEX deposits in Alaska, including the Lik, Red Dog, and Drenchwater deposits. They demonstrated that the compositions of spring and stream waters are strongly dependent upon the geologic characteristics of the deposits and their host rocks (grade of mineralization, proportion of iron sulfides in the ore, carbonate content of rocks in the watershed) and the extent of exposure of the deposits at the ground surface. Waters that drained Red Dog prior to mining were quite metal-rich (sum of dissolved base metals greater than 10 mg/l, and had variable pH values ranging from less than 4 to near 7. The reddish iron precipitates that form in streams in the area were partly responsible for the discovery of the deposit. The most acidic and metal-rich waters most likely reflect the abundance of base-metal sulfides in the ores (Kelley and Taylor, 1997). The high metal levels may also in part reflect the results of glaciation in the area within the last several thousand years, which exposed fresh, unweathered sulfides at the ground surface. Higher pH stream waters may reflect variable amounts of dilution by waters draining unmineralized rocks outside the main deposit (Kelley and Taylor, 1997), or variable amounts of carbonates in the ores or adjacent wallrocks. In contrast to Red Dog, the Lik deposit occurs in a watershed with abundant carbonate sedimentary rocks. As a result the natural stream waters have generally near-neutral pH values with relatively low to moderate metal concentrations. The Drenchwater deposit waters primarily drain pyrite-rich mineralization exposed at the surface. Due to the relatively low abundances of sulfide minerals other than pyrite in the Drenchwater rocks, the natural drainage waters, although acidic, have generally lower dissolved concentrations of Zn, Cu, and other metals than waters of similar pH draining sphalerite-, chalcopyrite-, and galena-rich mineral deposits (Kelley and Taylor, 1997).

W.R. Miller (unpub. data) has analyzed water samples collected from natural springs draining unmined SEDEX deposits in the Alaskan Brooks Range. Several of these samples are listed in the Appendix and shown on Figure 19.20. Miller (oral commun., 1996) attributes the extremely high dissolved metal concentrations of these waters to the exposure of the unweathered sulfides at the ground surface by glaciation, slow rates of weathering in the cold Arctic climate since the last glaciers retreated, and the residual concentration of the waters by partial freezing in the wintertime. The lower pH and higher metal concentrations of these spring waters compared to those of the stream waters (Fig. 19.20) suggests that dilution by surface waters draining unmineralized areas may be important in producing the range in pH of the stream waters.

Mississippi-Valley-Type (MVT) deposits

MVT deposits are lead- or zinc-rich deposits that are hosted by dolostones (predominant), limestones (less common) and sandstones (much less common) within continental sedimentary basins (see Leach and Sangster; 1993; Leach et al., 1995; and references therein). The deposits formed from heated basinal brines that migrate regionally away from mountain uplifts on basin edges (Leach and Sangster, 1993). The basinal brines deposit small amounts of sulfide minerals (iron sulfides, sphalerite, galena) regionally in the sedimentary aquifers through which they flow. The ore-grade mineral deposits form where zones of permeability allow focused mixing of brines from different aquifers, or flow of brines from one aquifer (such as a dolostone) into a chemically reactive different aquifer (such as a limestone) (Fig. 19.21). Although individual deposits are generally small, they occur in deposit clusters or districts that constitute world-class resources of lead and (or) zinc (Leach and Sangster,

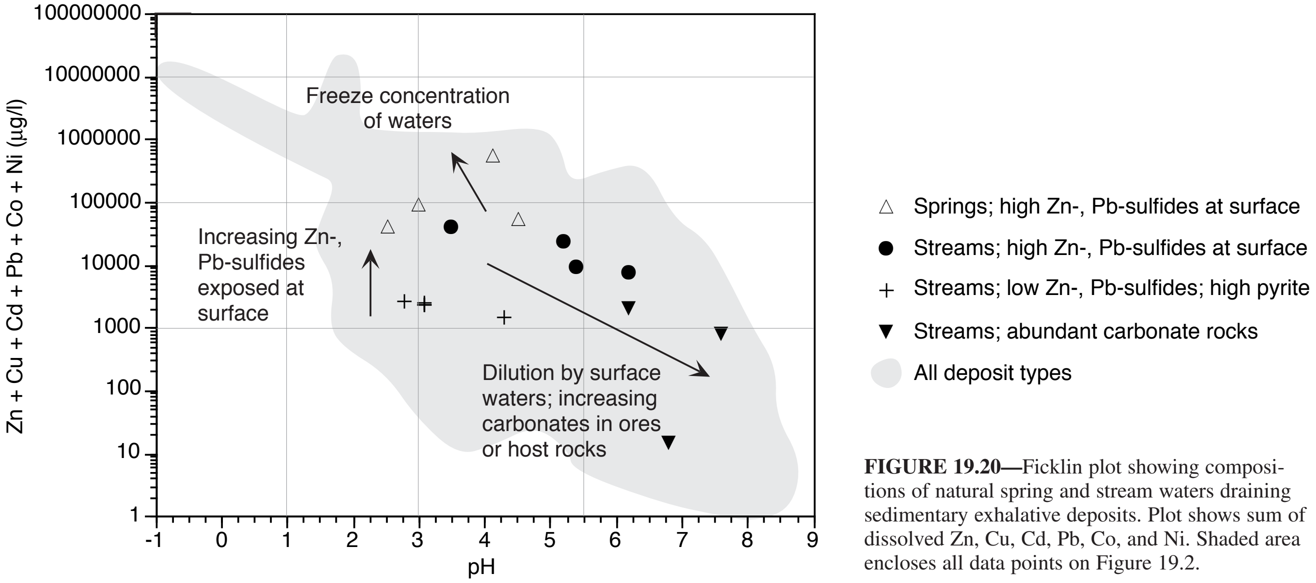

FIGURE 19.20—Ficklin plot showing compositions of natural spring and stream waters draining sedimentary exhalative deposits. Plot shows sum of dissolved Zn, Cu, Cd, Pb, Co, and Ni. Shaded area encloses all data points on Figure 19.2.

1993). Examples include the Old Lead Belt and Viburnum Trend (southeast Missouri), Tri-State (Missouri, Kansas and Oklahoma), Northern Arkansas, Upper Mississippi (Wisconsin), and Central Tennessee districts in the United States; Pine Point, Polaris, and Nanisivik in Canada; and, Silesia in Poland. Many of the deposits are zinc-rich with lesser lead; however, some deposits, such as the Viburnum Trend and Old Lead Belt districts in SE Missouri are predominantly lead-rich. Commodities other than lead and zinc which are variably produced from the deposits include silver, cadmium, germanium, barite, fluorite, and, rarely, nickel.

The ore and gangue mineralogy of the deposits is generally simple (Leach and Sangster, 1993; Leach et al., 1995), with predominant sphalerite, galena, pyrite, marcasite, dolomite, calcite, and quartz, and variable but lesser barite, chalcopyrite, bornite, enargite, and other sulfides. Ore mineral zoning is variable within individual deposits. Mineralogical variations within districts or deposits may reflect lack of occurrence of particular generations of mineralization; for example, some deposits in the Silesian MVT district contain a major late-stage botryoidal marcasite generation, whereas others do not (Viets et al., 1996).

Silicification (replacement of the dolostones and limestones by massive silica to form jasperoids), dolomitization (replacement of limestones by dolomite), and dissolution of the host carbonates (leading to large-scale solution collapse breccias) are the predominant alteration types in these deposits. In addition, formation of authigenic clay and feldspar minerals and destruction of detrital potassium-silicate minerals occurs in some districts.

The ores occur as open-space fillings in veins and breccias, and as replacements of the carbonate host rocks. The breccias may either be pre-mineralization karst breccias, or breccias created by carbonate dissolution during mineralization. Textures may vary substantially within a deposit, and include massive, fine-grained, very coarse grained (well-formed single crystals up to more than a meter in size), botryoidal, colloidal, and skeletal (Leach and Sangster, 1993).

In addition to the metals discussed previously, copper, nickel, cobalt, arsenic, and thallium are also enriched in some MVT deposits. For example, copper sulfides (bornite, chalcopyrite), and nickel and cobalt sulfides (such as millerite and vaesite) are relatively abundant in the SE Missouri districts, and are common as trace minerals in other MVT districts (Leach et al., 1995). The Silesian MVT deposits have strong enrichments of arsenic (as high as several percent) and thallium (as high as several thousands of ppm) in sphalerite and marcasite (Viets et al., 1996).

Predominant secondary minerals formed during pre-mining weathering of the deposits include iron oxides, cerussite (lead carbonate), anglesite (lead sulfate), smithsonite (zinc carbonate), and goslarite (zinc sulfate) (Leach et al., 1995). The reactivity of sulfides during post-mining weathering of MVT deposits is related to the sulfide mineralogy, texture, and trace-element content. Coarse-grained sphalerite and galena weather relatively slowly (galena to anglesite; sphalerite to goslarite), whereas botryoidal, arsenic-rich marcasite that occurs in a number of deposits weathers quite rapidly to a variety of secondary iron sulfates such as melanterite, copiapite, and others. For example, horn-shaped crystals of melanterite up to several cm long grow directly on As-rich marcasite in humid underground workings in a Silesian MVT deposit; the melanterite forms by the reaction of the As-rich marcasite with water vapor in the air. Acid generated by marcasite weathering may also enhance the reactivity of sulfides intergrown

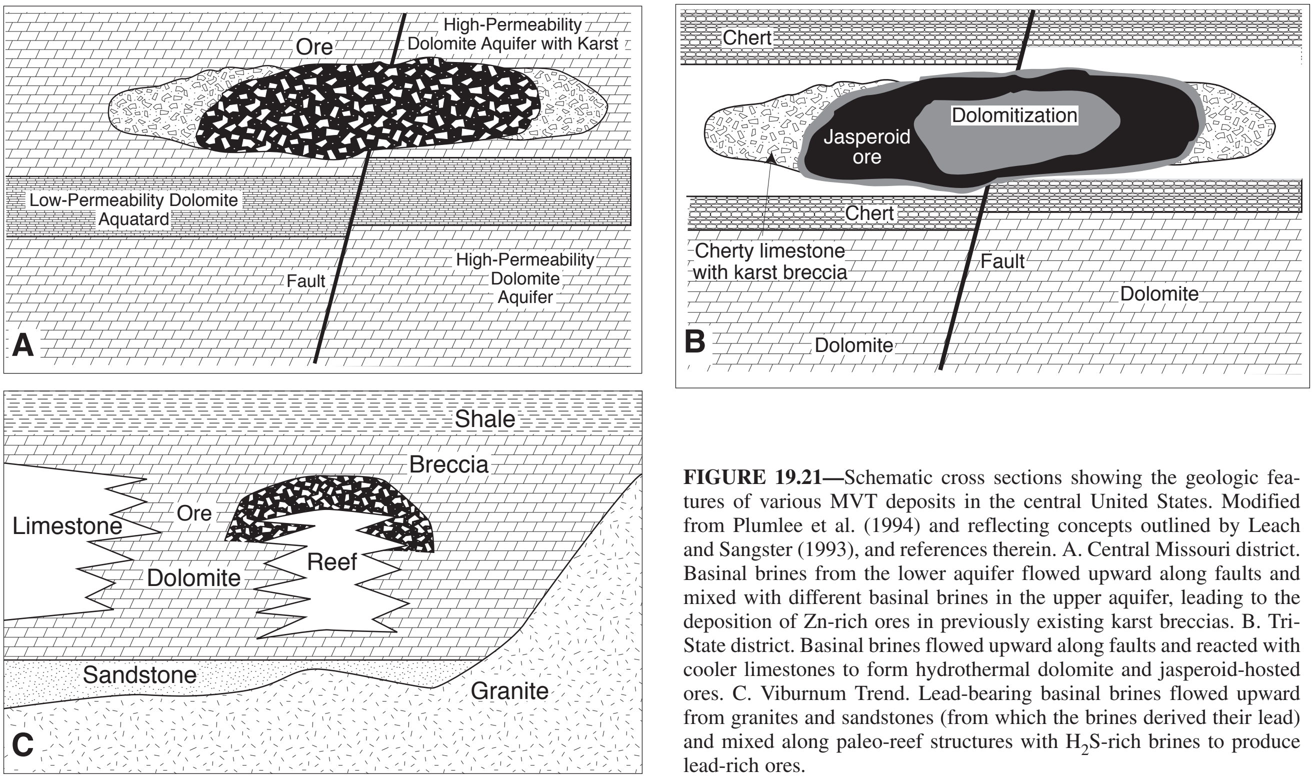

FIGURE 19.21—Schematic cross sections showing the geologic features of various MVT deposits in the central United States. Modified from Plumlee et al. (1994) and reflecting concepts outlined by Leach and Sangster (1993), and references therein. A. Central Missouri district. Basinal brines from the lower aquifer flowed upward along faults and mixed with different basinal brines in the upper aquifer, leading to the deposition of Zn-rich ores in previously existing karst breccias. B. Tri-State district. Basinal brines flowed upward along faults and reacted with cooler limestones to form hydrothermal dolomite and jasperoid-hosted ores. C. Viburnum Trend. Lead-bearing basinal brines flowed upward from granites and sandstones (from which the brines derived their lead) and mixed along paleo-reef structures with H_2S-rich brines to produce lead-rich ores.

with the marcasite. In humid underground stopes in the Viburnum trend, bornite without intergrown marcasite is quite unreactive, whereas bornite with intergrown marcasite weathers extensively to secondary copper sulfate salts.

Drainage-water compositions

Drainage waters listed in the Appendix include several collected from small, MVT deposits near Leadville, Colorado, as part of this study, and waters sampled by Barks (1977) from MVT tailings impoundments in the Old Lead Belt, SE Missouri. The Appendix also includes mine and tailings waters from the jasperoid-rich Tri-State, Missouri deposits (Smith and Schumaker, 1993). Although not included in the Appendix, a study currently underway is comparing mine waters from the Viburnum Trend with mine waters in the Polish Silesian deposits (D. Leach, J. Viets, oral commun., 1998).

From an environmental standpoint, the geology and mineralogy of MVT deposits are generally conducive to the formation of near-neutral drainage waters with generally low metal contents (Fig. 19.22). This is especially true in deposits with low iron-sulfide contents and (or) low amounts of jasperoid. In several MVT districts with low iron-sulfide and jasperoid contents, such as portions of the Viburnum Trend, mine waters are of sufficiently high quality that they are used as sources of potable waters for the mines and nearby towns (Leach et al., 1995); some near-neutral waters may have elevated lead concentrations as high as several hundred μg/l due to formation of lead-carbonate complexes. Moderately acidic and quite metalliferous (primarily zinc-rich) waters may form in iron-sulfide-rich ore bodies, in jasperoid ores, or in tailings impoundments where physical separation of sulfides from carbonates has occurred (Fig. 19.22). Near-neutral waters with elevated concentrations of dissolved Zn (as high as 100 mg/l) and Pb and Cd (several hundred μg/l) may form in mine workings with high iron sulfide contents; the iron sulfides generate acid waters, but the acid waters then are diluted by high-alkalinity waters draining the surrounding carbonate host rocks.

Preliminary water data collected from the As- and Tl-rich Silesian MVT deposits indicate that, although these trace metals occur in high levels in quite reactive marcasite and in sphalerite, their concentrations are very low in the mine waters (D. Leach, J. Viets, oral commun., 1997). Presumably, both the arsenic and thallium released by weathering of the sulfides form insoluble secondary minerals or are sorbed onto particulates.

Sediment-hosted (Carlin-type) Au deposits

Sediment-hosted Au deposits (also known as Carlin-type Au deposits) are large tonnage, low-grade deposits characterized by the occurrence of microscopic Au disseminated through large volumes of predominantly carbonate-rich, carbonaceous sedimentary host rocks (see Guilbert and Park, 1986; Hofstra et al., 1995; and references therein). Examples of sediment-hosted Au deposits include the Carlin, Jerritt Canyon, and Getchell trends in Nevada; within each trend, several major deposits are present.

Host rocks of the deposits are primarily carbonate sedimentary rocks, although in some deposits, such as Twin Creeks in the Getchell trend, the ores are hosted by cherty marine sediments and marine volcanics. Many of the deposits are localized beneath major thrust faults; black shales above the faults tended to serve as aquitards, and focused fluid flow in the underlying reactive carbonates.

The gold occurs primarily within arsenic-rich pyrite and marcasite, which commonly occur as microscopic overgrowths over diagenetic sulfides or as replacements of sedimentary iron oxides. Lesser amounts of gold occur in primary orpiment or realgar, in organic carbon, or in quartz (Hofstra et al., 1995). The realgar and orpiment can be quite coarse-grained, and are the most read-

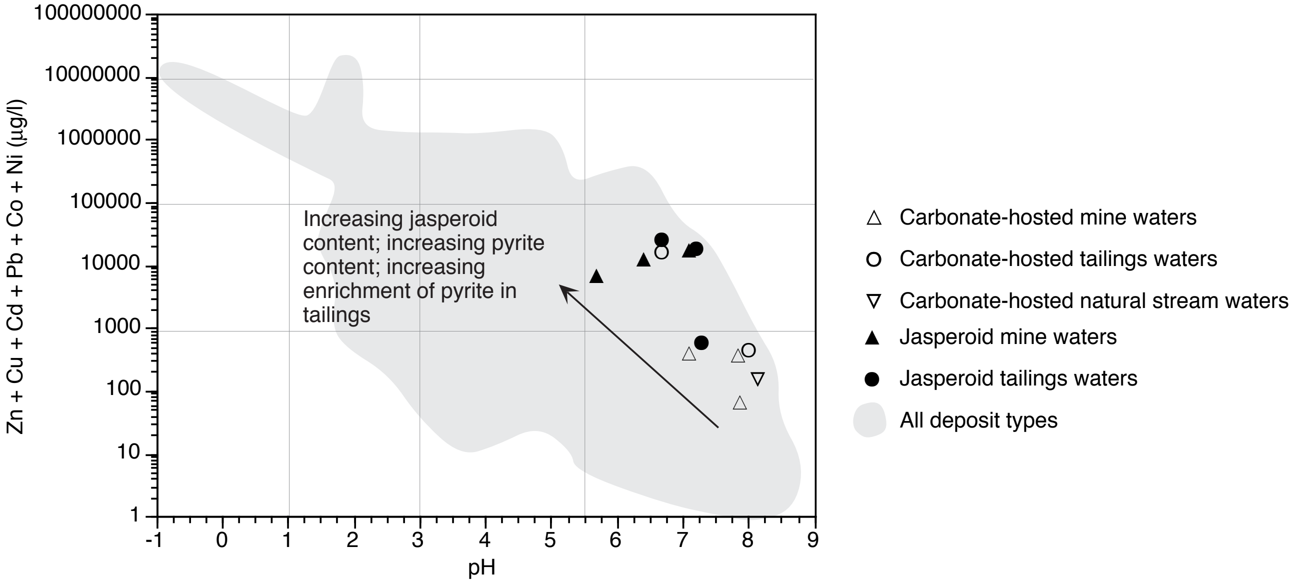

FIGURE 19.22—Ficklin plot showing compositions of mine waters, tailings waters, and a natural water draining carbonate-hosted and jasperoid-rich MVT deposits. Plot shows sum of dissolved Zn, Cu, Cd, Pb, Co, and Ni. Shaded areas encloses all data points on Figure 19.2.

ily visible ore minerals. Other primary hydrothermal minerals include calcite, dolomite, quartz, barite, cinnabar, and clays. In some deposits, late-stage, coarse grained botryoidal pyrite and marcasite are present.

As indicated by their primary mineralogy, sediment-hosted Au deposits are noted for their strong enrichments in arsenic. Other trace elements include many other of the "mobile epithermal" suite, including Hg, Sb, and Tl. Tungsten and selenium are also present. Base metals such as Zn, Cu, and Pb are conspicuously low in abundance. In deposits where black shales serve as aquitards, metals contained in the shales such as Mo, Co, Ni, U, and Se, may be environmentally important.

Hofstra et al. (1991) concluded that the Jerritt Canyon sediment-hosted Au deposits formed from moderately acidic, H_2S- and As-rich hydrothermal fluids that mixed with cooler, dilute, oxidized ground waters and reacted with Fe-bearing carbonate rocks. In the cores of the Jerritt Canyon deposits, where hydrothermal fluids flowed into the carbonate rocks from feeder fractures, extensive to complete decarbonatization (decalcification) of the host rocks and residual enrichment of silica occurred; this led to significant volume loss in the host rocks. Contemporaneous with the decarbonatization, deposition of hydrothermal quartz and realgar-orpiment veins, as well as sulfidation of Fe minerals in the host rocks occurred to produce the gold-bearing disseminated arsenian pyrite. Grading outward from the feeder zones, the extent of decarbonatization, realgar-orpiment veining, disseminated pyrite, and gold grades progressively decrease; this is accompanied by a progressive increase in the amount of carbonate remaining in the wallrock, as well as an increase in the amounts of pre-ore and ore-stage calcite veins (Hofstra et al., 1991; Hofstra et al., 1995). In deposits (such as Twin Creeks in the Getchell trend) where the ores occur within marine volcanic and siliceous sedimentary rocks, evidence of acid leaching and residual silica enrichment is also present.

Much of the sediment-hosted Au production to date in Nevada has come from the oxide ores. The dry climates in Nevada led to deep weathering of the ore bodies to produce secondary oxides such as hematite, goethite, and limonite, sulfates such as gypsum and celestite, and oxides of arsenic (scorodite, an Fe-As oxide) and antimony (stibiconite) (Hofstra et al., 1995). In these oxide ores, gold occurs in the iron oxides, in quartz, and on clay minerals. The occurrence of Au in the oxide ores makes them quite amenable to cyanide-heap leaching, a very cost-effective processing method. Increasingly, many deposits are producing gold from the non-oxidized ores (also known as refractory ores) that have high sulfide contents. These ores require special treatment such as roasting or biologically-enhanced oxidation in order to remove the sulfides and organic matter, followed by cyanidation.

Drainage-water compositions

Limited natural- and mine-drainage data are available for sediment-hosted Au deposits from a variety of literature sources. The Appendix includes data for several open-pit lakes (collected or compiled by Price et al., 1995) and ground water pumped from beneath and up hydrologic gradient from the Twin Creeks pits in the Getchell Trend (BLM, 1996). In addition to the data listed in the Appendix, Grimes et al. (1995) collected data from exploration drill holes along the Getchell trend in Nevada. Environmental impact statements submitted to agencies such as the Bureau of Land Management (BLM) are additional sources of natural ground water and mine-drainage data for a number of sediment-hosted deposits.

The data listed in the Appendix and shown on Figure 19.23 illustrate several important aspects of mine waters not only from these deposits, but also other deposits which have been completely oxidized prior to mining. Due to the acid-buffering effects of carbonate-rich host rocks and the low acid-generating potential of the oxide ores, all of the mine waters included in the Appendix have near-neutral pH values. However, unoxidized pyrite- and sulfide-rich ores in zones of intense decarbonatization may generate locally quite acidic waters. As would be expected from the major- and trace-element geochemistry of the deposits, the mine waters from sediment-hosted Au deposits generally have low concentrations of the base metals (Fig. 19.23), but relatively high concentrations of As (Fig. 19.23B). In addition to the data listed in the Appendix, several of the sediment-hosted pit waters have extremely high concentrations of Sb (as high as several mg/l) (BLM, 1996), and relatively high concentrations of Se (several

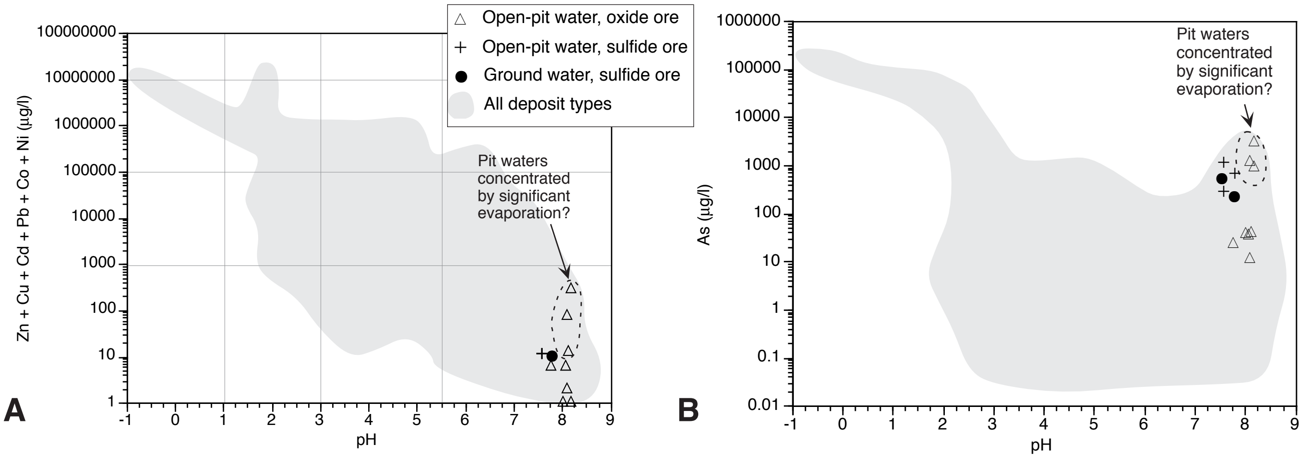

FIGURE 19.23—Plots of mine-water compositions for some sediment-hosted Au deposits. A. Ficklin diagram; B. Dissolved arsenic. Note differences in scale of the concentration axis between the plots. Shaded areas enclose all data points on corresponding Figures 19.1, 19.2.

tens of µg/l) (Price et al., 1995). At present, analytical data showing the concentrations of metals such as Mo, Co, Ni, and U in sediment-hosted Au deposit waters are quite sparse. However, these metals are relatively mobile in near-neutral pH waters, and may have source rocks in the black shales overlying many of the Nevada deposits. Hence, these metals may be present in measurable, possibly significant concentrations, and may have a source from outside the deposits themselves.

The arsenic concentrations measured in these deposits are among the highest measured in near-neutral waters draining all mineral deposit types. They likely reflect the desorption of arsenate species from particulates at higher pH in oxidized pit waters, and the high mobility of reduced arsenite species in reduced ground waters.

In general, waters in oxidized ores have lower metal and As concentrations than those in sulfide ores. The exceptions to this in the Appendix are the open pit waters from the oxide Boss deposit, Nevada, which have some of the highest concentrations of base metals (Cu, Pb in hundreds of µg/l) and As (as high as several mg/l) in mine water data we have compiled to date for this deposit type. The extreme chloride concentrations in the Boss waters (as high as 4300 mg/l) suggest that the Boss pit waters have undergone extensive evaporative concentration, which may be an explanation for the anomalously high As and base metal concentrations. However, leaching of Cl from the shales may have also contributed to the extreme chloride concentrations.

Magmatic sulfide deposits

Magmatic sulfide deposits are a subset of a broader class of mineral deposits known as magmatic segregation deposits. They are somewhat unusual among sulfide ore deposits in that they form by the segregation and crystallization of sulfide- and metal-rich immiscible liquids from crystallizing mafic magmas (Guilbert and Park, 1986; Cox and Singer, 1986; Foose et al., 1995; and references therein). The largest of these deposits are associated with layered mafic intrusions such as the Sudbury Complex, Ontario, Canada, the Duluth Complex, Minnesota, the Stillwater Complex, Montana, and the Bushveld Complex, South Africa. However, a number of smaller deposits can occur related to ultramafic volcanic rocks or ultramafic accumulations in Alpine ophiolite complexes (packages of sea floor rocks accreted to continents).

These deposits are characterized by massive lenses or bodies of sulfides; in some deposits, the sulfides fill in spaces around crystals of the associated host rock minerals. The mineralogy reflects the enrichments of S, Fe, Ni, Cu, Co,and platinum-group elements in the ores, and lesser enrichments of As, Pb, Zn, Te, and other trace elements. Pyrrhotite, pentlandite (a Fe-Ni sulfide), and chalcopyrite, are the dominant sulfides. Other sulfides include other Ni-sulfides (such as millerite), Ni- and Co- arsenides (such as gersdorffite), sphalerite, galena, and various gold-, silver-, and lead-telluride minerals (Foose et al., 1995).

The mafic and ultramafic host rocks of the deposits are characterized by coarse crystals of ferromagnesian minerals such as pyroxenes and olivine, and calcic plagioclase. Minor primary minerals include amphiboles, biotite, and magnetite. Other minerals such as talc, serpentine, actinolite, tremolite, calcite, epidote, and clays probably reflect hydrothermal alteration of the primary host rock minerals (Foose et al., 1995).

Drainage-water compositions

Foose et al. (1995) summarize mine-drainage compositions from the Duluth, Minnesota, and Stillwater Complex, Montana, collected from several sources, including SCS Engineers (1984), Feltis and Litke (1987), and Ritchie (1988). We have listed in the Appendix a sample collected by Eger (1992) from water draining a sulfide ore stockpile from the Duluth Complex. These data are summarized on Figure 19.24. In addition, Blowes and Ptacek (1994) list ranges of pH, Ni, and Al in the Nickel Rim tailings impoundment, Sudbury, Canada.

The range in pH of the drainage waters shown on Figure 19.24, from 4.5 to 7.7 (with most having pH greater than 6), is probably due to variations in the extent of interactions between acid waters generated by oxidation of sulfides and the reactive mafic and ultramafic host rock minerals such as olivine, pyroxenes, and plagioclase. The metal concentrations of the waters, especially those draining sulfide-rich Duluth Complex deposits, show enrichments of Ni (as high as 38 mg/l) and Cu (as high as 22 mg/l), reflecting the enrichments of Ni- and Cu-sulfides in the ores. Zinc concentrations are also high (up to several mg/l). The high concentrations of these metals in near-neutral pH waters most likely reflect the tendency of Ni and Zn not to sorb onto suspended particulates, and the formation of Cu-carbonate complexes that diminish the amounts of Cu that sorb onto particulates. Although no data are available, we speculate that other elements that are possibly enriched in the waters include Fe (in acidic or reduced waters), Mg, Ca, Co, and As, based on the abundance of these elements in the ores or host rocks. Waters that flow within massive sulfide lenses and that do not interact extensively with the surrounding host rocks most likely can generate highly acidic waters with extreme metal concentrations.

In their study of the Nickel Rim tailings impoundment, Blowes and Ptacek (1994) showed that pore waters in the vadose zone of the impoundment develop quite acidic pH values (as low as 2.1), but shift to higher pH with depth in the impoundment due to reactions with carbonate minerals that presumably are from the deposit host rocks. Dissolved nickel concentrations in the more acidic tailings waters are extreme (greater than 250 mg/l), but decrease to less than 10 mg/l at depth in the impoundment where the pH of the waters rises above 5.8. They attributed this to the sorption of the Ni onto secondary iron-hydroxide minerals in the impoundment. This indicates that sorption of Ni by secondary iron oxide coatings is more effective in the rock-dominated tailings environment than by suspended particulates in the water-dominated environment of mine-drainage streams (Smith et al., 1993).

Banded-iron formation (BIF) deposits

Banded-iron formations are the predominant source of iron worldwide. They are chemical sediments precipitated from ocean water, in which iron oxides (hematite, magnetite, limonite), iron carbonate (siderite), iron silicates (chlorite, greenalite, chamosite, grunerite, stilpnomelane), or iron sulfides (pyrite) are finely interlaminated or interbedded with chert or jasper (a ferruginous chert) (Guilbert and Park, 1986).

Two major types are recognized. Superior-type deposits do not have a clear link to submarine volcanism. In Superior deposits (such as the Mesabi Iron Range, Minnesota, the Marquette Iron Range, Michigan, and Minas Gerais, Brazil), the iron formation

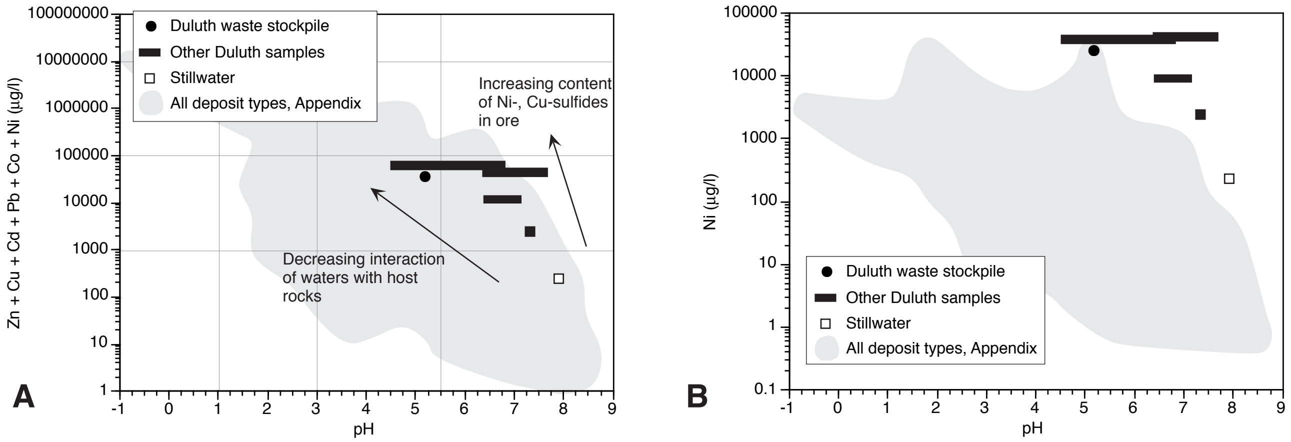

FIGURE 19.24—Plots of mine-drainage compositions for waters draining magmatic sulfide deposits. A. Ficklin diagram; B. Dissolved nickel. Note differences in scale of the concentration axis between the plots. Shaded areas enclose all data points on corresponding Figures 19.1, 19.2.

is interbedded with shallow marine sedimentary rocks indicative of deposition on continental shelves (Guilbert and Park, 1986; Cannon et al., 1995a; and references therein). In contrast, Algoma-type BIF deposits (such as the Vermillion Iron Formation, Minnesota, and Sherman Mine, Temagami, Ontario, Canada) are associated with marine volcanic rocks and are therefore likely related genetically to submarine volcanic-hydrothermal processes such as those that produced volcanogenic massive sulfide deposits (Guilbert and Park, 1986; Cannon et al., 1995b; and references therein). Both types of deposits are laterally extensive, extending for many kilometers along strike, and up to tens of hundreds of meters thick.

In many deposits a characteristic zoning in the iron minerals is present reflecting location in the ocean basin, and hence oxidation conditions of the ocean waters at time of formation (James, 1954). Oxide facies were deposited in the near-shore environment, with hematite closest to shore. Toward progressively deeper water, first magnetite and then iron silicates (in the form of amorphous iron silicates) and iron carbonate facies were deposited. In the deepest portions of the basin, sulfide facies iron formation was deposited in areas where the ocean waters became anoxic. Subsequent metamorphism has led to the recrystallization of the ores, with the biggest effect being the formation of fibrous iron silicates such as greenalite, amosite, and minnesotaite.

Weathering of the BIF deposits resulted in leaching of the silica and residual enrichment of the iron. The bulk of the world's BIF iron production has come first from weathered oxide and silicate facies ores, and subsequently from the unweathered, oxide and silicate facies (or taconite) ores (Guilbert and Park, 1986; Cannon et al., 1995b). Relatively little production has come from the carbonate facies or sulfide facies, except where weathering has left behind only secondary iron oxides; however, all facies may be present in a given deposit.

Drainage-water compositions

We have seen only rare mention in the literature of mine-drainage waters from BIF deposits. To date, we have only found one partial analysis of mine waters from Algoma-type BIF deposits in the Sherman Mine, Temagami, Ontario, Canada (Shelp et al., 1994). The open pit water sampled by Shelp et al. (1994) is clearly from sulfide facies rocks, given the low pH (3.0) of the waters. Given its low pH, the water contains relatively low concentrations of dissolved iron (10 mg/l), manganese (4 mg/l), and the base metals Ni, Cu, and Zn (hundreds of µg/l). These metal variations presumably reflect the abundance of pyrite with low trace metals in the sulfide facies rocks. Trace metal contents of waters draining sulfide facies in Superior-type deposits may have even lower base metal concentrations than those measured by Shelp et al. (1994), due to the generally lower contents of these trace metals in Superior-type deposits. Although generally a minor component of the producing BIF deposits, sulfide facies ores, where present, may pose a potential source of acid-rock drainage.

In general, mine waters draining the much more prevalent oxide, silicate, and carbonate facies BIF ores are likely to have near neutral pH with very low concentrations of metals. This is due to the non-acid-generating nature of the ore and gangue minerals. Pit waters from an oxide-facies iron formation deposit are of sufficiently high quality that they are used as for municipal water supply (W. Day, written commun., 1998).

Low-sulfide, gold-quartz vein deposits

Low-sulfide, gold-quartz vein deposits (also known as mesothermal lode gold and Mother-Lode-type deposits) have been an important source for gold historically, and continue to be explored for and produced in many geologically favorable parts of the world. Examples include the Juneau Gold Belt and Fairbanks, Alaska; Mother Lode, California; Abitibi Belt, Superior Province, Canada; Yellowknife, Northwest Territories, Canada; Kalgoorlie, Australia; and Muruntau, Uzbekistan (see summaries in Guilbert and Park, 1986; Hodgson, 1993; Goldfarb et al., 1995; and references therein).

The ore occurs as native Au in quartz veins in medium-grade greenstone metamorphic rocks (usually metamorphosed basalts, but metamorphosed sediments, ultramafic or felsic volcanic rocks, or granitic intrusive rocks may also host deposits). The veins contain less than 2–3 volume percent sulfides (typically pyrite and (or) arsenopyrite, with variable but lesser stibnite, chalcopyrite, pyrrhotite, sphalerite, galena, and tetrahedrite). Carbonate minerals, including siderite, ankerite, calcite, or iron-rich dolomite, may be present in the veins.

Wallrock alteration away from the veins is extensive, and includes abundant silicification, carbonatization, and sulfidation; the same sulfide and carbonate minerals present in the veins are introduced as alteration minerals into the surrounding host rocks. Sericite alteration may be also present adjacent to some veins, and grades laterally outward into propylitic alteration containing chlorite and epidote (Goldfarb et al., 1995).

Mineral zoning is generally uncommon. Sulfides in the wallrock are generally fine-grained, although large arsenopyrite masses may be locally present.

The deposits weather to limonite, leaving behind the quartz. Scorodite, an Fe-As oxide, may also form locally (Goldfarb et al., 1995).

Drainage-water compositions

Goldfarb et al. (1997), Cieutat et al. (1994), and Trainor et al. (1996) present excellent summaries of the geologic controls on mine-drainage compositions from Alaska mesothermal Au deposits. A subset of their data are included in the Appendix.

As with other deposit types having abundant carbonate gangue or carbonate alteration, these vein deposits typically generate mine waters with near-neutral pH values (Fig. 19.25). However, quite acidic pH waters can develop in mine tailings or ore stockpiles, presumably due to the physical enrichment of pyrite and other sulfides. Due to the low base metal sulfide contents of the veins, the near-neutral-pH waters typically have relatively low dissolved base metal concentrations, although vein ores with high pyrite contents and sphalerite contents may generate waters with higher dissolved Zn concentrations of several mg/l. Due to the abundance of arsenopyrite, As is present in mine waters, typically in elevated concentrations ranging from several μg/l to 100 μg/l.

Alkalic Au-Ag-Te vein deposits

Alkalic Au-Ag-Te vein deposits have provided significant gold production historically and continue to be the focus of exploration and development. They are spatially and genetically associated with explosive magmatic features (such as diatremes or breccia pipes) in alkalic igneous intrusive complexes. Very large, high grade deposits (such as Cripple Creek, Colorado) may occur; lower-grade vein or disseminated deposits are also common. Other examples include Ladolam, Lihir Island; Emperor, Fiji; Boulder County, Colorado; Ortiz, New Mexico; and Zortman Landusky, Montana. See references such as Thompson et al. (1985), Cox and Bagby (1986), Ahmad et al. (1987), Kelley et al. (1995), and references therein for detailed discussions of the geology of these deposits.

The deposits are characterized by high-grade quartz dominant veins, and low-grade disseminations surrounding the veins (Kelley et al., 1995). Important vein ore minerals include Au- and Ag-telluride minerals such as calaverite and sylvanite, native Au and native Te, and other tellurides; other sulfides include fine-grained pyrite, chalcopyrite, sphalerite, galena, tetrahedrite, stibnite, and occasional cinnabar. Vein gangue minerals include fluorite, adularia, chlorite, calcite, dolomite, barite, celestite (a strontium sulfate), hematite, magnetite, and roscoelite (a vanadium mica).

The disseminated deposits contain native Au, fine-grained auriferous pyrite, occasional telluride minerals, quartz, abundant fine-grained adularia, and fluorite (Kelley et al., 1995).

Wallrocks adjacent to veins are altered to a variable mixture of dolomite, adularia, sericite, roscoelite, magnetite and pyrite. The disseminated deposits are characterized by intense, pervasive alteration of the host rocks to very fine-grained adularia, sanidine, orthoclase, pyrite, ± sericite.

Drainage-water compositions

The Appendix contains limited data collected in this study from the Cripple Creek and Eldora, Colorado districts. The

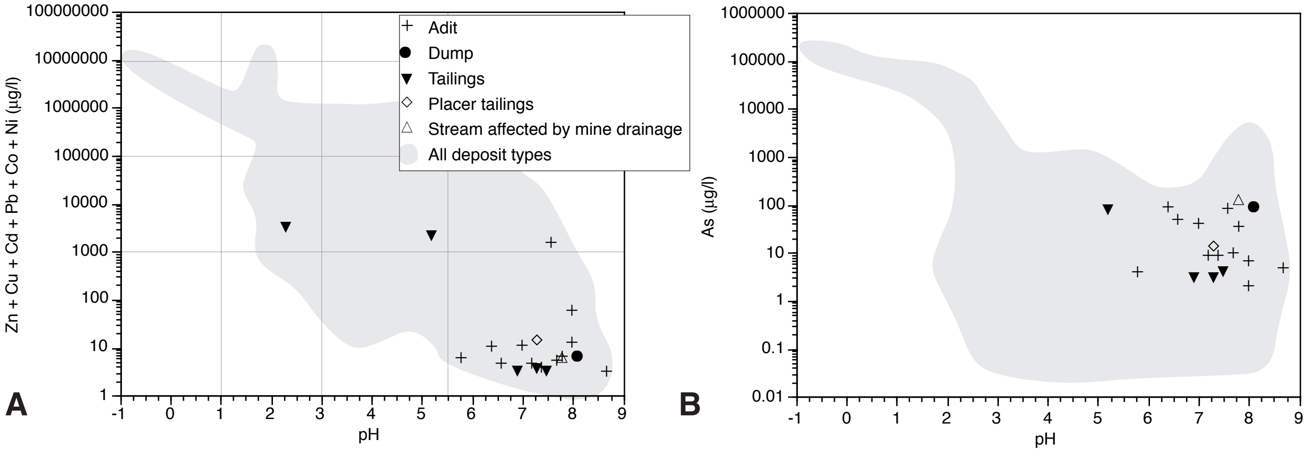

FIGURE 19.25—Plots of mine-drainage and stream compositions for waters draining low-sulfide, Au quartz vein deposits. A. Ficklin diagram; B. Dissolved arsenic. Note differences in scale of the concentration axis between the plots. Shaded areas enclose all data points on corresponding Figures 19.1, 19.2.

Carlton Tunnel drains all of the underground workings in the central Cripple Creek district, and so reflects an integrated drainage signature for much of the deposit.

As a result of their generally low sulfide contents and high carbonate contents, these deposits tend to generate near-neutral pH waters with low dissolved base-metal concentrations (Fig. 19.26). It is possible that pyrite-rich ore zones may generate locally acidic waters. However, these disseminated pyrite zones are commonly associated with flooding of the host rocks by fine-grained potassium feldspar. It is interesting to note that acid-base accounting tests of pyrite-rich disseminated ores at Cripple Creek showed that these pyrite- and feldspar-rich ores are non-acid generating, possibly due to the acid-neutralizing capacity and reactivity of the fine-grained feldspars (Cripple Creek mine geologist, oral commun., 1994).

The Carlton Tunnel waters draining Cripple Creek are rather unusual in their chemistry and physical characteristics. They are unusually warm (23°C) and have very high chloride concentrations (22 mg/l) compared to most other mine-adit waters we have measured. As the tunnel drains more than 1000 m vertical extent of mine workings, the warmer water temperatures presumably reflect the geothermal gradient of rocks within the mine. The warmer temperatures of the waters, coupled with their elevated chloride concentrations suggest that the waters may have undergone evaporative concentration in the underground mine workings. The Carlton Tunnel waters, as discussed previously in the section on geochemical controls, are calculated to be at, or above, saturation with a variety of carbonates, zeolites, and feldspars. All of these minerals are noted to form in evaporative playa-lake deposits. Although the carbonates are likely influencing some aspects of the water chemistry, further studies of the suspended particulates are needed to investigate whether zeolites and feldspars are present, and, if they are, whether or not they are influencing the water chemistry. Further studies are also warranted to determine if evaporative concentration is occurring within the underground workings. Although the Carlton Tunnel waters have very low dissolved metals, their volume is sufficiently large (in excess of several million gallons per day) that the total metal loadings leaving the tunnel are substantial.

Sandstone U deposits

Sandstone U deposits include both tabular and roll-front types. As the name implies, they are typically hosted by continental sandstones, which are frequently interbedded with or form channels within redbed shales. Both types of deposits form by the leaching of uranium from U-rich source rocks (such as volcanic rocks or sediments derived from granites) by oxidizing ground waters in the vadose zone, followed by precipitation of the uranium and other elements when the ground waters encounter either organic matter or reduced ground waters at the water table. Repeated oxidation, dissolution, and re-precipitation of the reduced ores by successive volumes of ground waters leads to the formation of ore grade deposits. For details, see several papers on sandstone deposits of the western United States in Ridge (1968), summaries such as Fischer (1974) and Turner-Peterson and Hodges (1986), and references therein. Related deposit types that form by similar processes include redbed Cu deposits (Lindsey et al., 1995) and solution-collapse breccia pipe U deposits (Wenrich et al., 1995).

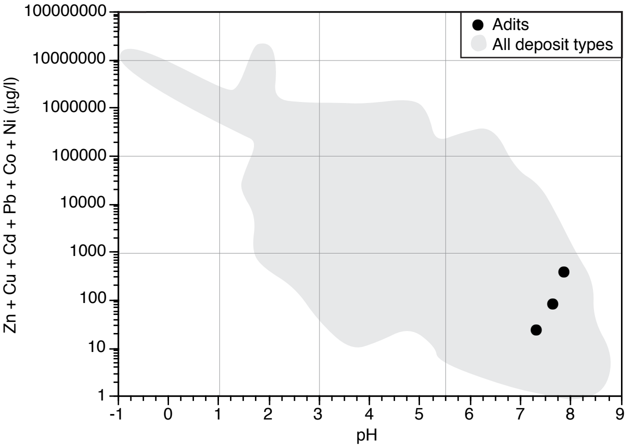

FIGURE 19.26—Ficklin plot showing sum of dissolved Zn, Cu, Cd, Pb, Co, and Ni in adit waters draining Au-Ag-Te vein deposits. Shaded area encloses all data points on Figure 19.2.

In addition to U, other elements typically but variably enriched in sandstone U deposits include V, Mo, Se, Cu, Ag, Ni, Co, Cr, As, and Pb. In the tabular deposits, primary uranium minerals (uraninite, coffinite), Fe-sulfides (pyrite, marcasite), reduced vanadium minerals (such as montroseite, doloresite, corvusite), ± Cu-sulfides (primarily chalcocite), ± Ag sulfides replace detrital organic matter within the sandstones; minor sphalerite, galena, and other sulfides may also be present locally. In the roll- front deposits, the oxidized ground waters travel down dip through the vadose zone; upon reaching the reduced conditions of the water table they precipitate reduced uranium minerals (uraninite, coffinite) and iron sulfides, with lesser amounts of Cu- and Ag-sulfides. The roll-front deposits derive their name from the u-shaped cross sections of the deposits, with the round part of the u pointing down dip in the direction of ground-water flow. Calcium carbonate is common in both deposit types as a cement in the host sandstones. Redbed Cu deposits (Lindsey et al., 1995) form in much the same way as sandstone U deposits, except that the source-rock materials leached by the ground waters are Cu-rich rather than U-rich.

Minerals formed in the oxidized zones of these deposits include a complex assemblage of oxidized uranium and vanadium minerals (such as carnotite, tyuyamunite, torbernite, uranophane, hewettite, and many others), copper carbonates (malachite and azurite), hydrous Cu- and Fe-sulfates, and Fe oxides.

Drainage-water compositions

The Appendix summarizes limited mine water data from the Monument Valley and Cameron districts, Arizona (Longsworth, 1994). In both these districts, the ore deposits are hosted by sandstone channels within redbed shales, and the ore minerals replace organic detrius within the sandstones (Malan, 1968). The Monument Valley and Cameron district water compositions (Longsworth, 1994) reflect the deposit geology and the dry climate and alkaline ground waters typical of the southwestern U.S. desert. The open pit waters and ground waters affected by open pit mining (Fig. 19.27) have quite high pH values (from 6.5–9.5), high chloride contents indicative of evaporative concentration,

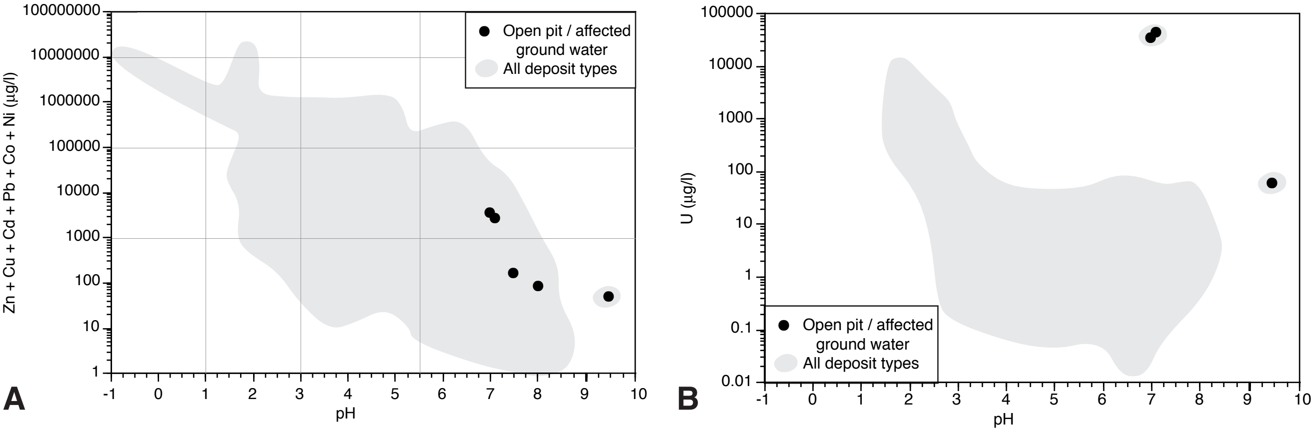

FIGURE 19.27—Compositions of open pit waters and ground waters affected by open-pit mining for sediment-hosted U deposits. A. Ficklin diagram; B. Dissolved uranium. Note differences in scale of the concentration axis between the plots. Shaded areas enclose all data points on corresponding Figures 19.1, 19.2.

and can have exceptionally high concentrations of dissolved U (as high as several tens of mg/l) and other metals that are both enriched in the deposits and mobile in near-neutral to alkaline waters, such as Ni (hundreds of µg/l), Co (1–2 mg/l), Mo (several mg/l), and Zn (1 mg/l). Although not measured, Se and As concentrations in the waters are probably elevated as well.

SUMMARY

The empirical data that we have collected and compiled for waters draining diverse mineral-deposit types underscore the roles that deposit geology, climate, mining- and mineral-processing method, geochemical processes, and other factors play in controlling the compositions of mine waters, tailings waters, and natural waters draining unmined mineral deposits.

The geologic characteristics of a mineral deposit ultimately set the stage for the compositions of waters that drain the deposit both prior to mining and as a result of mining and mineral processing if appropriate remedial practices were not followed. Important geologic characteristics that influence drainage compositions include:

- The amounts of iron sulfides in the deposit, alteration and host rocks, and their reactivities to near-surface weathering processes.
- The amounts of other sulfides in the deposit, wallrock alteration, and host rocks.
- The amounts and reactivities of acid-buffering carbonates and other minerals in the deposit, wallrock alteration, and host rocks, and their reactivities to near-surface weathering processes.
- The textures and trace-element contents of the ore, gangue, alteration, and host rock minerals, which influence their reactivities.
- The trace-element content of the deposit, wallrock alteration, and host rocks. The same trace elements that are enriched in the deposit, alteration, or host rocks are typically enriched in the drainage waters if the elements occur in readily-weathered mineral phases.
- The ore type (vein, massive, disseminated) and hydrogeologic characteristics of the deposit and host rocks (structures, permeability of host rocks), which control the access of ground water and atmospheric oxygen to the deposit.
- The spatial distribution of ore types, mineralogic zones, alteration zones, rock types, or other geologic characteristics within a mineral deposit, each of which may produce drainage waters with characteristic ranges in pH and metal concentration.
- The extent of pre-mining oxidation, which converts acid-generating iron sulfide minerals to a variety of non-acid-generating secondary minerals.

Geochemical processes (such as sulfide oxidation, mineral precipitation, and sorption), biogeochemical processes (such as bacterially catalyzed oxidation of aqueous iron), physical processes (such as evaporation) and hydrologic processes (such as dilution by non-mineralized ground or surface waters) play crucial roles in determining the composition of mine- and natural-drainage waters.

Climate, mining method, and mineral processing method also influence drainage compositions, although generally to a lesser extent than deposit geology or geochemical, biogeochemical, physical, and hydrologic processes. Climate influences include the extent of pre-mining oxidation of sulfides, the extent and periodicity of evaporation of drainage waters, and the amounts of ground and surface waters with which the drainage waters mix. The mining method used influences the extent to which the ores and wastes interact with atmospheric oxygen and ground or surface waters. The mineral processing method further influences the accessibility of weathering agents to mine wastes. For example, the higher acidities and metal contents of waters collected from tailings impoundments compared with those of mine waters has been demonstrated for several mineral-deposit types.

Empirical studies as a predictive tool

Our study has compiled empirical data for natural- and mine-drainage waters spanning only a portion of the potential deposit types and climates that are present worldwide. Some inferences about potential compositions of natural and mine-drainage waters in deposit types and climates for which data are not available may be made by drawing analogies to the most geologically similar deposit types and climates for which drainage data are available. However, further data compilations are clearly necessary, both within deposit types and climates covered by this study, as well as those not covered by this study.

Nonetheless, our results show that, by understanding the geology of a mineral deposit and the other factors that influence mine-drainage compositions, it is possible to constrain the potential ranges in pH and ranges in metal concentrations of mine- and natural-drainage waters that may develop within different mineralogic zones, ore types, or alteration types in a given mineral deposit. Our results are not sufficiently precise, however, that they can be used to quantitatively predict the exact compositions of water that will develop in a particular mine, mine dump, or tailings impoundment at a particular mineral deposit. Instead, results of geologically constrained empirical studies such as ours can be used to help anticipate the potential formation of problematic mine-drainage waters before they develop, so that they can be prevented or mitigated with appropriate engineered solutions (thereby helping active and proposed mines and mineral processing facilities meet regulations requiring zero or minimal discharge of metals into the environment), Empirical studies of waters draining unmined mineral deposits are also useful to help constrain drainage compositions that were present in geologically and climatically similar mineralized areas prior to mining, thereby providing another tool for estimating pre-mining environmental baseline conditions.

The results of this study also suggest that some geologic features of mineral deposits, such as carbonate-bearing rocks or wallrock alteration, may be potentially useful in the development of lower-cost mine-drainage remediation technologies.

Our study does not address in detail the possible downstream impacts of drainage waters if they are released into the environment from naturally weathering mineral deposits, from past producing mines, or accidentally from active mines or mineral processing facilities. These effects are a complex function of

- The relative volumes of the drainage waters compared to the volumes of stream or ground waters with which they mix.
- The compositions of the drainage waters relative to those of the waters with which they mix (a function of the climate and geology of the watershed surrounding the deposit).
- Geochemical, biogeochemical, and physical processes that occur downstream or down hydrologic gradient from the deposit, such as formation of particulates, sorption of metals onto (or desorption from) particulates, settling of particulates, photolytic reactions, and reactions of waters with bed sediments or aquifer minerals.

Empirical studies of mineral deposits in the context of their surrounding watersheds are thus an important and needed next step in the development of improved predictive methods to help anticipate, mitigate, and remediate the potential environmental effects of mineral-resource development.

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APPENDIX

This appendix is a compilation of dissolved compositions of mine waters and natural waters draining diverse mineral deposit types. Most mine, mine-dump, and tailings data were collected from past producing sites. The data included were either collected during this study, or were compiled from data published in the literature. The data are grouped according to deposit type and, for a given deposit type, further grouped according to ore zone, alteration zone, or mineralogic zone within the deposit.

Abbreviations for water type are as follows: a-adit; mg-groundwater from underground mine; d-mine dump; ms-seep affected by mining activity; t-tailings water; ts-seep affected by tailings waters; op-pond or lake in open pit; os-seep affected by open-pit waters; og-ground water affected by open-pit mining; mst-stream affected by mine drainage waters; ns-natural seep; nst-stream affected by natural drainage waters. Sites we know to be currently under remediation are noted by “r”. Tailings water compositions listed here do not include measured concentrations of cyanide and organic chemicals.

The data contained in this compilation were determined by a variety of analytical methods, which we have indicated whenever possible using different type styles. Anions were determined using ion chromatography. Major cations and trace metals were determined by a variety of techniques, including flame or graphite furnace AA (shown in plain type), ICP-AES (bold type), or ICP-MS (italic type). In a few data sets compiled from the literature, no analytical methods were documented; in these cases, plain type was used for all elements listed. Negative concentration values indicate that the species or element was present in the sample, but in concentrations below the analytical detection limit. Samples marked with an asterisk have metal concentrations measured in mg/l or µg/l units; those without asterisks were measured in generally equivalent ppm or ppb units. These and other sources of uncertainty in the data and interpretations are discussed in the Summary of Data and Methods section.

Deposit type *Ore / alteration type* Sample	Description	Water Type	Reference
Volcanogenic massive sulfide (VMS)			
Kuroko-type, hosted by volcanic rocks			
*Rich-90WA103	Richmond Mine, Iron Mtn., California	a, r	Alpers and Nordstrom (1991)
*Rich-90WA108	Richmond Mine, Iron Mtn., California	a, r	Alpers and Nordstrom (1991)
*Rich-90WA109	Richmond Mine, Iron Mtn., California	a, r	Alpers and Nordstrom (1991)
*Rich-90WA110A	Richmond Mine, Iron Mtn., California	a, r	Alpers and Nordstrom (1991)
*LMG	Les Mines Gallen, Rouyn Noranda, Quebec	ms	Rao et al. (1994)
Hol-511	Holden, Washington, USA	t	Kilburn and Sutley (1997)
Hol-528	Holden, Washington, USA	t	Kilburn and Sutley (1997)
Hol-529	Holden, Washington, USA	t	Kilburn and Sutley (1997)
Hol-534	Holden, Washington, USA	a	Kilburn and Sutley (1997)
Hol-548	Holden, Washington, USA	d	Kilburn and Sutley (1997)
Hol-549A	Holden, Washington, USA	t	Kilburn and Sutley (1997)
Hol-549B	Holden, Washington, USA	t	Kilburn and Sutley (1997)
Besshi-type, hosted by sedimentary and intermediate submarine volcanic host rocks			
Duch-1	Duchess Mine, Latouche Island, Alaska	a	Goldfarb et al. (1996)
Duch-2	Duchess Mine, Latouche Island, Alaska	t	Goldfarb et al. (1996)
Black-18A	Blackbird Mine, Latouche Island, Alaska	t	Goldfarb et al. (1996)
Beat-16	Beatson Mine, Latouche Island, Alaska	t	Goldfarb et al. (1996)
V-Ely-1	Creek downstream from Ely Mine, Vermont	mst	This study
Besshi-type, hosted by graphitic schists			
FC-3	Adit, Fontana Creek, Tennessee	a	This study
SUG-1 0.2	Sugar Mine, Tennessee	a	This study
Cobalt-rich, hosted by metamorphosed sediments			
*BB25	Cobalt, Idaho	os, r	McHugh et al. (1987)
High sulfidation (quartz alunite epithermal)			
Acid-sulfate alteration			
AD-3	Reynolds Adit, Summitville, Colorado	a, r	This study; Plumlee et al. (1995b)
AD-3	Reynolds Adit, Summitville, Colorado	a, r	This study; Plumlee et al. (1995b)
AD-3	Reynolds Adit, Summitville, Colorado	a, r	This study; Plumlee et al. (1995b)
AD-3	Reynolds Adit, Summitville, Colorado	a, r	This study; Plumlee et al. (1995b)
AD-3	Reynolds Adit, Summitville, Colorado	a, r	This study; Plumlee et al. (1995b)
AD-1435C	Reynolds Adit, Summitville, Colorado	a, r	This study; Plumlee et al. (1995b)

Deposit type *Ore / alteration type* Sample	Description	Water Type	Reference
Chand-1	Chandler Adit, Summitville, Colorado	a, r	This study; Plumlee et al. (1995b)
Chand-1	Chandler Adit, Summitville, Colorado	a, r	This study; Plumlee et al. (1995b)
Chand-1	Chandler Adit, Summitville, Colorado	a, r	This study; Plumlee et al. (1995b)
Dike 2	Cropsy Waste Dump, Summitville, Colorado	d, r	This study; Plumlee et al. (1995b)
550D-R	Cropsy Waste Dump, Summitville, Colorado	d, r	This study; Plumlee et al. (1995b)
North Dump	North Waste Dump, Summitville, Colorado	d, r	This study; Plumlee et al. (1995b)
N Dump S Seep	North Waste Dump, Summitville, Colorado	d, r	This study; Plumlee et al. (1995b)
SC12	Tailings impoundment, Summitville, Colorado	t, r	This study; Plumlee et al. (1995b)
Blackstrap	Seep in open pit, Summitville, Colorado	o, r	This study; Plumlee et al. (1995b)
SOB-1 Seep	Seep in open pit, Summitville, Colorado	o, r	This study; Plumlee et al. (1995b)
IOWA-1	Seep below Iowa Adit, Summitville, Colorado	a, r	This study; Plumlee et al. (1995b)
SPIT-1 Pond	Snowmelt pond in South Pit, Summitville, Colorado	o, r	This study; Plumlee et al. (1995b)
SPIT-2 Pond	Snowmelt pond in South Pit, Summitville, Colorado	o, r	This study; Plumlee et al. (1995b)
NPIT-1 Pond	Snowmelt pond in North Pit, Summitville, Colorado	o, r	This study; Plumlee et al. (1995b)
Ch Seep	Seep near Chandler Adit, Summitville, Colorado	ms	This study; Plumlee et al. (1995b)
Missionary East	Seep near Reynolds Adit, Summitville, Colorado	ms	This study; Plumlee et al. (1995b)
Sh-1	Seep in mine waste pile, Summitville, Colorado	d, r	This study; Plumlee et al. (1995b)
TD Seep	Seep, Summitville, Colorado	ms	This study; Plumlee et al. (1995b)
AREA L	Seep in mine waste pile, Summitville, Colorado	d, r	This study; Plumlee et al. (1995b)
lkp fa	Longfellow-Kohler pond, Red Mtn. Pass, Colorado	a	This study
long 1 fa	Longfellow Tunnel, Red Mtn. Pass, Colorado	a	This study
3R-1	Stream below 3R Mine, Patagonia Mtns., Arizona	ms	This study
*EC91AP16	Mt. Macintosh, Vancouver, British Columbia	nst	Koyanagi and Panteleyev (1994)
*EC91AP19	Mt. Macintosh, Vancouver, British Columbia	nst	Koyanagi and Panteleyev (1994)
*EC91AP22	Mt. Macintosh, Vancouver, British Columbia	nst	Koyanagi and Panteleyev (1994)
*EC91AP24	Mt. Macintosh, Vancouver, British Columbia	nst	Koyanagi and Panteleyev (1994)
*EC92AP-21	Mt. Macintosh, Vancouver, British Columbia	nst	Koyanagi and Panteleyev (1994)
Propylitic alteration			
Missionary West	Seep near Reynolds Adit, Summitville, Colorado	ms	This study
Cordilleran Lode			
Advanced-argillic to quartz-sericite-pyrite alteration			
*Berkeley Pit Surface	Butte, Montana	op	Davis and Ashenberg (1989)
*Berkeley Pit 3 meters	Butte, Montana	op	Davis and Ashenberg (1989)
*Berkeley Pit 100 meters	Butte, Montana	op	Davis and Ashenberg (1989)
Hot Spring S-Au			
Shallow acid-sulfate alteration			
*82WA119	Leviathan, California	a	Ball and Nordstrom (1989)
*81WA132C	Leviathan, California	a	Ball and Nordstrom (1989)
*82WA118	Leviathan, California	a	Ball and Nordstrom (1989)
Climax-type Porphyry Mo			
Potassic, quartz-sericite-pyrite, greisen alteration			
mcn 1 fa	McNulty Dump, Climax, Colorado	d, r	This study
mcn 2 fa	McNulty Dump, Climax, Colorado	d, r	This study
Porphyry Cu, Cu-Mo			
Quartz-sericite-pyrite alteration			
*MW Weir 3	Mt. Washington, British Columbia	op	Kwong (1991)
*MW Weir 1	Mt. Washington, British Columbia	op	Kwong (1991)

Deposit type *Ore / alteration type* Sample	Description	Water Type	Reference
*MW BH89-14	Mt. Washington, British Columbia	og	Kwong (1991)
*MW BH89-4	Mt. Washington, British Columbia	og	Kwong (1991)
*MW BH89-3	Mt. Washington, British Columbia	og	Kwong (1991)
*MW BH89-10	Mt. Washington, British Columbia	og	Kwong (1991)
*MW BH89-8	Mt. Washington, British Columbia	og	Kwong (1991)
*MP1W1, Globe	Globe, Arizona	og	Eychaner (1988)
TMT-29	Alamosa River basin, Colorado	ns	Barry (1996)
TMT-28	Alamosa River basin, Colorado	ns	Barry (1996)
TMT-38	Alamosa River basin, Colorado	ns	Barry (1996)
Propylitic alteration			
*MW BH89-2	Mount Washington, British Columbia	og	Kwong (1991)
*MW BH89-13	Mount Washington, British Columbia	og	Kwong (1991)
Algoma Banded Fe Formation			
Sulfide-facies			
*Sherman S Pit	South Pit, Sherman Mine, Temagami, Ontario	op	Shelp et al. (1994)
Polymetallic veins			
Zn, Pb, ± Cu-rich			
St.Kev	St. Kevin's Gulch, Colorado	a	Smith (1991)
St.Kev	St. Kevin's Gulch, Colorado	a	Smith (1991)
PENN1.1	Pennsylvania Mine, Summit County, Colorado	a	This study
SHO1.1	Shoe Basin Mine, Summit County, Colorado	a	This study
Au-quartz-pyrite			
DRUID1FA.45	Druid Mine, Central City, Colorado	ms	This study
Druid shaft	Druid Mine, Central City, Colorado	a	This study
Argo 1 fa	Argo Tunnel, Central City, Colorado	a, r	This study
Argo 1 fa.1	Argo Tunnel, Central City, Colorado	a, r	This study
ARGO1.1	Argo Tunnel, Central City, Colorado	a, r	This study
VC1A.1	Idaho Mine, Central City, Colorado	a	This study
VC1B.1	Idaho Mine, Central City, Colorado	a	This study
Pyrite-rich; Zn, Pb, Cu-poor			
PMB193 FA .2	Pass Me By Mine, Alamosa River, Colorado	a	This study
PMB1FA.1	Pass Me By Mine, Alamosa River, Colorado	a	This study
Burnt Adit	Burnt Creek Mine, Alamosa River basin, Colorado	a	This study
Burnt Dump	Burnt Creek Mine, Alamosa River Basin, Colorado	d	This study
ARC FA .2	Alamosa River Canyon, Colorado	ns	This study
Fe Spring, Fe Crk	Iron Creek, Alamosa River Basin, Colorado	ns	This study
Burnt Spring	Burnt Creek, Alamosa River Basin, Colorado	ns	This study
SMCB1FA.1	Unnamed adit, South Mineral Creek, Creede, Colorado	ns	This study
Carbonate-rich, or in rocks altered to contain carbonate			
CHAP3FA.45	Chapman Gulch, Ophir, Colorado	a	This study
CHAP2FA.1	Seep, Chapman Gulch, Ophir, Colorado	ns	This study
bon 1 fa	Bonner Mine, Mineral Creek Basin, Colorado	a	This study
MIZ FA .2	Mizer Mine, Alamosa River Basin, Colorado	a	This study
ASIA FA .2	Asiatic Mine, Alamosa River Basin, Colorado	a	This study
CARC-1 FA .2	Unnamed adit 1, Carson Camp, Colorado	a	This study
CARC-3 FA .2	Unnamed adit 3, Carson Camp, Colorado	a	This study
CARC-2 FA .2	Unnamed adit 2, Carson Camp, Colorado	a	This study
ns1 fa	North Star Mine, Silverton, Colorado	a	This study
para up fa	Paradise Portal, Ophir Pass., Colorado	a	This study

Deposit type *Ore / alteration type* Sample	Description	Water Type	Reference
Para 1 fa	Adit near Paradise Portal, Ophir Pass., Colorado	a	This study
BUR FA .2 8/1	Burley Tunnel, Silver Plume, Colorado	a, r	This study
NATL FA .2 8/	National Tunnel, Blackhawk, Colorado	a	This study
NTUN1.1	National Tunnel, Blackhawk, Colorado	a	This study
GAM6FA.1	Gamble Gulch, Gilpin County, Colorado	ns	This study
MC1FA.1	Unnamed adit, Miners Creek, Creede, Colorado	a	This study
Creede-type epithermal			
Carbonate-poor			
AL1FA.1	Alpha Corsair, Creede, Colorado	a	This study
SOL1FA.1	Solomon, Creede, Colorado	a	This study
Carbonate-rich, or in propylitically altered rocks			
RAW1FA.1	Rawley 12 Adit, Bonanza, Colorado	a	This study
*Rawley	Rawley 12 Adit, prior to collapse, Bonanza, Colorado	a	Moran (1973)
*Rawley	Rawley 12 Adit, prior to collapse, Bonanza, Colorado	a	Moran (1973)
*Rawley	Rawley 12 Adit, prior to collapse, Bonanza, Colorado	a	Moran (1973)
Raw1 (Rawley 12)	Rawley 12 Adit, Bonanza, Colorado	a	This study
ML-ad	Minnie Lynch Mine, Bonanza, Colorado	a	This study
ML-FP	Minnie Lynch Mine, Bonanza, Colorado	a	This study
ML-1	Minnie Lynch Mine, Bonanza, Colorado	d	This study
Rawley 3 seep	Rawley 3 Adit, Bonanza, Colorado	d	This study
KC tail	Kerber Creek Tailings, Bonanza, Colorado	t, r	This study
Am 1 fa	American Tunnel, Silverton, Colorado	a, r	This study
Magmatic sulfide			
Massive iron-, nickel-, and copper-sulfide lenses in ultramafic rocks			
*DUL	Waste stockpile, Duluth Complex, Minnesota	d	Eger (1992)
Polymetallic replacement and skarns			
Sandstones and other carbonate-poor host rocks			
*Eagle 1610	Eagle Mine, Gilman District, Colorado	a, r	Engineering Science, Inc. (1985)
*Eagle 1610	Eagle Mine, Gilman District, Colorado	a, r	Engineering Science, Inc. (1985)
*Eagle 1610	Eagle Mine, Gilman District, Colorado	a, r	Engineering Science, Inc. (1985)
*Eagle Chief	Eagle Mine, Gilman District, Colorado	a, r	Engineering Science, Inc. (1985)
*Eagle Chief	Eagle Mine, Gilman District, Colorado	a, r	Engineering Science, Inc. (1985)
Igneous-hosted ores			
GAM4FA.1	Tip Top, Gilpin County, Colorado	a	This study
YAK1FA.1	Yak Tunnel, Leadville, Colorado	a, r	This study
GAR1FA.1	Garibaldi Mine, Leadville, Colorado	a	This study
Calc-silicate skarns			
*Glngar GW-1	Glengarry Mine, New World, Montana	a	Pioneer Technical Services (1994)
*Glngar GW-2	Glengarry Mine, New World, Montana	a	Pioneer Technical Services (1994)
*Glngar SW-2	Glengarry Mine, New World, Montana	d	Pioneer Technical Services (1994)
*McLar	McLaren Mine, New World, Montana	d	Pioneer Technical Services (1994)
Carbonate-hosted, pyrite-rich			
BAN1FA.1	Bandora Mine, Silverton, Colorado	a	This study
LD1FA.1	Leadville Drain, Leadville, Colorado	a	This study
FG1.1	French Gulch, Breckenridge, Colorado	ms	This study
kok fa	Kokomo Mine, Climax, Colorado	a	This study
Carbonate-hosted, pyrite-poor			
Anon1 fa.1	Anonymous mine #1, Park City, Utah	a	This study

Deposit type *Ore / alteration type* Sample	Description	Water Type	Reference
Anon2 fa	Anonymous Mine #2, Park City, Utah	a	This study
*FishCk1	Fisher Creek Adit, New World, Montana	a	Pioneer Technical Services (1994)
*Blkwar	Black Warrior Mine, New World, Montana	a	Pioneer Technical Services (1994)
*LilDaisy	Little Daisy Mine, New World, Montana	a	Pioneer Technical Services (1994)
Sedimentary-exhalative (SEDEX)			
Hosted by shales and cherts with no carbonates			
*#2016, Alaska (natural)	Unnamed deposit, Alaska	ns	W. R. Miller, unpub. data
*#2019, Alaska (natural)	Unnamed deposit, Alaska	ns	W. R. Miller, unpub. data
*#2015, Alaska (natural)	Unnamed deposit, Alaska	ns	W. R. Miller, unpub. data
*#2021, Alaska (natural)	Unnamed deposit, Alaska	ns	W. R. Miller, unpub. data
DW010	Drenchwater Creek deposit, Brooks Range, Alaska	nst	Kelley and Taylor (1997)
DW017	Drenchwater Creek deposit, Brooks Range, Alaska	nst	Kelley and Taylor (1997)
DW018	Drenchwater Creek deposit, Brooks Range, Alaska	nst	Kelley and Taylor (1997)
DW024	Drenchwater Creek deposit, Brooks Range, Alaska	nst	Kelley and Taylor (1997)
DW026	Drenchwater Creek deposit, Brooks Range, Alaska	nst	Kelley and Taylor (1997)
RD 23	Red Dog deposit, Brooks Range, Alaska	nst	Kelley and Taylor (1997)
RD33	Red Dog deposit, Brooks Range, Alaska	nst	Kelley and Taylor (1997)
RD42	Red Dog deposit, Brooks Range, Alaska	nst	Kelley and Taylor (1997)
RD44	Red Dog deposit, Brooks Range, Alaska	nst	Kelley and Taylor (1997)
Hosted by shales, cherts, and carbonates			
LK57	Lik Deposit, Brooks Range, Alaska	nst	Kelley and Taylor (1997)
LK61	Lik Deposit, Brooks Range, Alaska	nst	Kelley and Taylor (1997)
LK62	Lik Deposit, Brooks Range, Alaska	nst	Kelley and Taylor (1997)
Mississippi-Valley-Type (MVT)			
Jasperoid-poor			
*Site 4-Drill (mean)	Bonehole, Old Lead Belt, SE Missouri	ms	Smith and Schumacher (1993)
*Site 5 (mean)	Desloge, Old Lead Belt, SE Missouri	ts	Smith and Schumacher (1993)
*Site 8 (mean)	Elvins, Old Lead Belt, SE Missouri	ts	Smith and Schumacher (1993)
DAU1.FA.1	Dauntless Mine, Mt. Sherman, Colorado	a	This study
RUB1.RA	Ruby Mine, Weston Pass, Colorado	a	This study
WP2FA.1	Weston Pass, Colorado	nst	This study
Abundant jasperoid			
*Map # 101	St. Regis Mine, Tri-State District, Missouri	mg	Barks (1977)
*Map #105	Vogey Mine, Tri-State District, Missouri	mg	Barks (1977)
*Map # 109	Sunset Mine, Tri-State District, Missouri	mg	Barks (1977)
*Map # 14	Orongo, Tri-State District, Missouri	ts	Barks (1977)
*Map #16	Orongo, Tri-State District, Missouri	ts	Barks (1977)
*Map # 17	Webb City, Tri-State District, Missouri	ts	Barks (1977)
Sediment-hosted Au			
Primarily oxide ore			
*Boss 4/1/94	Boss Pit, Esmerelda County, Nevada	o	Price et al. (1995)
*Boss Pit 7/1/94	Boss Pit, Esmerelda County, Nevada	o	Price et al. (1995)
*Boss Pit 12/26/94	Boss Pit, Esmerelda County, Nevada	o	Price et al. (1995)
*Cortez East, 6/15/92	Cortez Pit, Carlin, Nevada	o	Price et al. (1995)
*Cortez Middle, 6/15/92	Cortez Pit, Carlin, Nevada	o	Price et al. (1995)
*Cortez West, 6/15/92	Cortez Pit, Carlin, Nevada	o	Price et al. (1995)
*Big Springs 5/30/95	Big Springs Pit, Jerritt Canyon, Nevada	o	Price et al. (1995)
*Big Springs 4/13/95	Big Springs Pit, Jerritt Canyon, Nevada	o	Price et al. (1995)

Deposit type *Ore / alteration type* Sample	Description	Water Type	Reference
Primarily sulfide ore, carbonate-poor host rocks			
*DW-06, 12/22/94	South Pit, Twin Creeks, Nevada	og-ng?	BLM (1996)
*DW-06, 12/22/94	South Pit, Twin Creeks, Nevada	og-ng?	BLM (1996)
*DW-07,12/22/94	South Pit, Twin Creeks, Nevada	og-ng?	BLM (1996)
*394318-1,6/14/95	near West Pit, Twin Creeks, Nevada	ng-og?	BLM (1996)
*394319-2,8/17/95	near South Pit, Twin Creeks, Nevada	ng-og?	BLM (1996)
Low-sulfide Au-quartz veins			
LCk2	Little Creek Prospect, Kenai Fjords Natl. Park, Alaska	mst	Cieutat et al. (1994)
SF6	Sonny Fox Mine, Kenai Fjords Natl. Park, Alaska	a	Cieutat et al. (1994)
Goy13	Goyne Prospect, Kenai Fjords Natl. Park, Alaska	a	Cieutat et al. (1994)
McKin2	McKinley Lake Dist., Chugach Natl. Forest, Alaska	a	Trainor et al. (1996)
McKin5	McKinley Lake Dist., Chugach Natl. Forest, Alaska	a	Trainor et al. (1996)
McKin11	McKinley Lake Dist., Chugach Natl. Forest, Alaska	a	Trainor et al. (1996)
McKin13	McKinley Lake Dist., Chugach Natl. Forest, Alaska	a	Trainor et al. (1996)
McKin19	McKinley Lake Dist., Chugach Natl. Forest, Alaska	a	Trainor et al. (1996)
Ind1	Independence Mine, Willow Creek District, Alaska	t	Goldfarb et al. (1996)
Ind2	Independence Mine, Willow Creek District, Alaska	a	Goldfarb et al. (1996)
GC4	Gold Cord Mine, Willow Creek District, Alaska	t	Goldfarb et al. (1996)
HG6	High Grade Mine, Willow Creek District, Alaska	a	Goldfarb et al. (1996)
HG7	High Grade Mine, Willow Creek District, Alaska	t	Goldfarb et al. (1996)
HY16	Hi-Yu tailings, Fairbanks District, Alaska	t	Goldfarb et al. (1996)
Ch21	Christina Mine, Fairbanks District, Alaska	a	Goldfarb et al. (1996)
Pt22	Placer Tailings, Cleary Crk., Fairbanks, Alaska	pt	Goldfarb et al. (1996)
Sc23	Scrafford mine, Fairbanks district, Alaska	d	Goldfarb et al. (1996)
M27	Mexican mill tailings, Juneau District, Alaska	t	Goldfarb et al. (1996)
Eb28	Ebner Mine, Juneau District, Alaska	a	Goldfarb et al. (1996)
AJ29	Alaska-Juneau Mine, Juneau District, Alaska	a	Goldfarb et al. (1996)
Alkalic Au-Ag-Te veins			
CAR1FA.1	Carlton Tunnel, Cripple Creek, Colorado	a	This study
hur 1 fa	Huron Adit, Eldora, Colorado	a	This study
swa 1 fa	Swathmore Adit, Eldora, Colorado	a	This study
Sediment-hosted U			
*MVD-1	Moonlight Mine, Monument Valley district, Arizona	og	Longsworth (1994)
*MVD-2	Moonlight Mine, Monument Valley district, Arizona	og	Longsworth (1994)
*MVSW-1	Moonlight Mine, Monument Valley district, Arizona	op	Longsworth (1994)
*3T-529	Manuel Denetstone #3 Mine, Cameron district, Arizona	og	Longsworth (1994)
*JSW-1	Jeepster #1 Mine, Cameron district, Arizona	op	Longsworth (1994)

Deposit type *Ore / alteration type* Sample	Temp. °C	Spec. Cond. µS/cm	Alk. mg/l $CaCO_3$	pH	Diss. O_2 ppm	SO_4 mg/l	F mg/l	Cl mg/l	Al mg/l	As µg/l
Volcanogenic massive sulfide (VMS)										
Kuroko-type, hosted by volcanic rocks										
*Rich-90WA103	35			0.48		118000			**2210**	**56400**
*Rich-90WA108	42			-0.35		420000			**4710**	**169000**
*Rich-90WA109	32			-0.7		360000			**6680**	**154000**
*Rich-90WA110A	42			-1		760000			**1420**	**340000**
*LMG				1.8					3520	50000
Hol-511	15	4420		2.9		1400	1		*8.4*	*-1*
Hol-528	8	5600		2.9		1700	2	2	*>10*	*-1*
Hol-529	5	2680		3.1		860		1	*>10*	*-1*
Hol-534	4.5	840		4.5		340	0.6	3	*2.4*	*-1*
Hol-548	3	960		4.6		340	0.7	1.7	*2.2*	*1*
Hol-549A	16	16000		3.1		12000	7		*>10*	*1*
Hol-549B	18	37500		2.8		39700	60		*>10*	*1*
Besshi-type, hosted by sedimentary and intermediate submarine volcanic host rock										
Duch-1	7	320	20	6.1	9.5	166	0.07	3.8	0.015	
Duch-2	12	790		2.9	9	197	0.07	4	>3	
Black-18A	10	822	-10	3.1	8	311	0.4	3.7	>3	
Beat-16	7	146	38	6.7	5	31	0.07	3.4	0.004	
V-Ely-1	21.5	1046		2.98	9	352	0.16	0.51	**14**	
Besshi-type, hosted by graphitic schist										
FC-3	14	73.2		5.45	6.5	23	0.06	0.48	-0.5	*-1*
SUG-1 0.2	13	286		4.98	6	103	0.16	0.55	**1.8**	*-1*
Cobalt-rich, hosted by metamorphosed sediments										
*BB25				4.38		2400	2.4	21	54	39
High sulfidation (quartz alunite epithermal)										
Acid sulfate alteration										
AD-3	4	2100		3.16		2200			**112**	360
AD-3	4.5	3200		2.94	10	1920		4.7	**130**	**400**
AD-3	4	5400		2.72	10	4530			**290**	*2900*
AD-3						4510	-0.5	2.2	**230**	*790*
AD-3	4	1800		3.23	10	**1650**	**0.67**	**6.5**	**150**	*130*
AD-1435C	4	10		3.25	-	2133			**160**	*460*
Chand-1	4	7110		2.37	10	15000	3.7	1.0	**430**	*3900*
Chand-1	6	5530		2.77	12	**6250**	**0.99**	**1.5**	**340**	*1500*
Chand-1	4	5820		2.92	12	**12600**	**1.6**	**1.3**	**310**	*2500*
Dike 2	6	10300		2.31	10	23000		26	**2350**	*5700*
550D-R	13.5	7650		2.52	10	8370			**890**	*190*
North Dump						3800	1.7	2	**260**	*-40*
N Dump S Seep	7.5	7500		2.41	10	**11300**	**3.3**	**2.5**	**710**	*160*
SC12	14.5	4100		2.9	10	3360			**200**	*110*
Blackstrap	~14	38000		1.75		125800		240	**5380**	**15000**
SOB-1 Seep	18	19500		1.71	10	29850			**2100**	*28000*
IOWA-1	5	2800		2.79	10	1900	-0.5	2.0	**190**	*18*
SPIT-1 Pond	19	3300		2.48	10	2320	0.70	1.3	**140**	*690*
SPIT-2 Pond	19	4600		2.41	10	7890	-0.25	2.2	**290**	*3400*
NPIT-1 Pond	14	2510		2.73		2140	1.1	0.59	**180**	*110*
Ch Seep	3	3670		3.01	10	**5000**	**-0.5**	**0.51**	**280**	*82*
Missionary East	5	1450		3.84	4.5	**1540**	**0.51**	**1.1**	**120**	*200*
Sh-1	8	5090		3.41	6	**7310**	**1.2**	**27**	**210**	*-20*

Deposit type *Ore / alteration type* Sample	Temp. °C	Spec. Cond. µS/cm	Alk. mg/l $CaCO_3$	pH	Diss. O_2 ppm	SO_4 mg/l	F mg/l	Cl mg/l	Al mg/l	As µg/l
TD Seep	4	858		3.76	3	**425**	**0.23**	**10**	**5**	*190*
AREA L	10	3090		2.51	10	4820	1.2	2.4	**110**	*78*
lkp fa	16	3600		2.61	10	1740			**60**	*6700*
long 1 fa	3.5	1900		3.11	5	660	2.9		**11**	*1400*
3R-1	20.3	971		3.2	12	489	0.48	5.8	**52**	
*EC91AP16	13.1	163.2		3.9		31			2	
*EC91AP19	13.7	176.5		3.8		39			2	
*EC91AP22	9.4	244		3.5		50			6	
*EC91AP24	9.1	53.9		3.7		228			16	
*EC92AP-21	28.9	2400		2		1300			46	
Propylitic alteration										
Missionary West	5	374	100	6.84	1	**110**	**0.41**	**0.52**	*0.07*	*-20*
Cordilleran Lode										
Advanced-argillic to quartz-sericite-pyrite alteration										
*Berkeley Pit Surface				2.86		3850		12	126	30
*Berkeley Pit 3 meters				2.8		5740		9	152	50
*Berkeley Pit 100 meter				3.08		7060		20	206	700
Hot Spring S/Au										
Shallow acid-sulfate alteration										
*82WA119				1.85		11200	5.1	9.2	623	41000
*81WA132C				2.45		5400			440	27100
*82WA118				1.8		7540	3.4	8.4	438	35000
Climax-type Porphyry Mo										
Potassic, quartz-sericite-pyrite, greisen alteration										
mcn 1 fa	4	6800		1.86	10	4340	710		**960**	*6*
mcn 2 fa	5	4700		1.9	10	2570	379		**590**	*5*
Porphyry Cu, Cu/Mo										
Quartz-sericite-pyrite alteration										
*MW Weir 3	8.3			3.48		226			7.2	-50
*MW Weir 1	4.8			3.59		696			22	-50
*MW BH89-14	7.9			3.84		50.9			1.5	-50
*MW BH89-4	5.4			3.65		608			10.7	-50
*MW BH89-3	5			4.37		445			9.3	-50
*MW BH89-10	5.8			5.66		406			0.07	310
*MW BH89-8	6.6			4.64		452			0.93	310
*MP1W1, Globe				3.6		8800	0.3	340	250	-5
TMT-29	6.4	2540		2.3	12	407	0.9	1.1	**66**	*1*
TMT-28	5.4	1430		2.8	4	1010	1.8	0.1	**70**	*1*
TMT-38	8.9	10860		2.28	12	13400	8.4	3.6	**390**	*44*
Propylitic alteration										
*MW BH89-2	3.6		11.3	6.5		15.9			-0.05	-50
*MW BH89-13	5.4		172	6.9		192			-0.05	120
Algoma Banded Fe Formation										
Sulfide-facies										
*Sherman S Pit				3		1500	1.4	7	10	

Deposit type *Ore / alteration type* Sample	Temp. °C	Spec. Cond. µS/cm	Alk. mg/l $CaCO_3$	pH	Diss. O_2 ppm	SO_4 mg/l	F mg/l	Cl mg/l	Al mg/l	As µg/l
Polymetallic veins										
Zn, Pb, ± Cu-rich										
St.Kev				2.72		1290			19	8
St.Kev				2.67		1150			16	7
PENN1.1	5	1300		3.65	6				20	*-20*
SHO1.1	2.5	770		3.62	10	440	1	0.5		*-20*
Au-quartz-pyrite										
DRUID1FA.45	10	6000		2.75	9.5	5300	-0.5	10	430	*180*
Druid shaft	14	6660		2.63	8	7200	5.5	8.3	**98**	*180*
Argo 1 fa				2.72	10				**29**	*150*
Argo 1 fa.1				2.65					**23**	*120*
ARGO1.1	17	4000		2.93	10	2100			**25**	*91*
VC1A.1	10	3300		4.65	0.078	2000	3.1	7.2	4.7	*-20*
VC1B.1	9	3300		4.2	2	1980	2.9	4.7	5.8	*-20*
Pyrite-rich; Zn, Pb, Cu-poor										
PMB193 FA .2	6	1100		3.02	0.1	630	0.38	0.75	**59**	*33*
PMB1FA.1	4.5	1200		3.02	0.075	660	0.3	1.1	51	*24*
Burnt Adit				3.1		220	0.55	0.56	**5**	*-3*
Burnt Dump				4.83		320	1.1	0.33	**2**	*-3*
ARC FA .2	9	2600		2.75	11.8				**38**	*-1*
Fe Spring, Fe Crk				2.94		220	0.2	0.48	**9**	*-3*
Burnt Spring				3.82		1300	5.3	1.6	**31**	*-3*
SMCB1FA.1	11.5	750		3.09	4	490	0.01	0.51	21	*0.05*
Carbonate-rich, or in rocks altered to contain carbonate										
CHAP3FA.45		1000		6.9	0.1	700	-0.1	0.9	0.1	*-1*
CHAP2FA.1	8	2000	62	7.58	0.1	920	0.01	2.1	0.028	**-2**
bon 1 fa	5.5	920		3.09	8	330	0.6	0.7	**5**	*-2*
MIZ FA .2	7.5	620		5.85	3.6	264	0.6	0.39	*0.05*	*-1*
ASIA FA .2	9	480		6	10	163	0.25	0.33	**1**	*-1*
CARC-1 FA .2	4	840		3.47	1.5	500	0.54	0.43	**17**	*-3*
CARC-3 FA .2	5	400		6.46	0.6	140	0.26	0.35	*0.06*	*6*
CARC-2 FA .2		410		6.04	9	180	0.3	0.18	*0.2*	*-3*
ns1 fa	8	860		6.57	9	310	1.5	1.9	**7**	*-2*
para up fa	6	2000		5.86	0.002	1110			**2**	*-2*
Para 1 fa	5	2200		5.37	0.002	1270	5.1	1.4	**13**	*36*
BUR FA .2 8/1	8	1000		5.7	7.5	430	1.1	18	**1**	*-3*
NATL FA .2 8/	8	1500		5.36	6	900	-0.05	2.4	*0.007*	*-3*
NTUN1.1	6	1400		6.18	5	810			0.5	2
GAM6FA.1	5.5	470		6.74	8.0	185	-0.1	0.5	0.02	0.05
MC1FA.1	12	340	58	6.7	7	75	0.01	1.05	0.01	15
Creede-type epithermal										
Carbonate-poor										
AL1FA.1	10	730		4.37	10	290	-0.1	2	**5**	*15.4*
SOL1FA.1	7.5	790		4.45	9	260	-0.1	0.6	1.1	0.05
Carbonate-rich, or in propylitically altered rocks										
RAW1FA.1	9.5	1100	61	5.96	0.1	600	0.7	-0.1	0.4	8
*Rawley			0	3.6						5
*Rawley		900	0	3.4						

Deposit type *Ore / alteration type* Sample	Temp. °C	Spec. Cond. µS/cm	Alk. mg/l $CaCO_3$	pH	Diss. O_2 ppm	SO_4 mg/l	F mg/l	Cl mg/l	Al mg/l	As µg/l
*Rawley	9.5	1050	0	3.5					0.88	
Raw1 (Rawley 12)	9.5	1200		5.67	1	700	1.3	0.54	**2**	*8.5*
ML-ad	7	840		5.97	-1	440	1.1	0.84	*0.14*	*44*
ML-FP	5	700		5.93	-1	230	1.5	0.86	*0.02*	*5.5*
ML-1	11	1100		2.84	10	620	1.2	0.8	11.00	-1
Rawley 3 seep	6.5	820		2.82	10	230	0.6	0.36	**3**	*7.4*
KC tail	22	4890		2.37	10	12200	6.7	1.3	**200**	*2300*
Am 1 fa	12	2400		6.59	10	1270	5.7		**7**	*-2*
Magmatic sulfide										
Massive iron-, nickel-, and copper-sulfide lenses in ultramafic rocks										
*DUL			3	5.2		820				
Polymetallic replacement and skarns										
Sandstones and other carbonate-poor host rocks										
*Eagle 1610	20.9	5400		4.84		7770		9.5		1000
*Eagle 1610		9300		**4.8**		9530		7.8	16	
*Eagle 1610		8880	-5	**4.5**		9600		6.8	11	-1250
*Eagle Chief	10.3	1290		3.59		1405		5.7		-2500
*Eagle Chief		4370		**3.9**		3340		5.4	2.8	
Igneous-hosted ores										
GAM4FA.1	8	880		3.78	7.5	300	-0.1	2.7	5	0.05
YAK1FA.1	9	980		4.44	7.5	593	1.3	1.1	3	1.7
GAR1FA.1	4.5			4.76	5	75	0.2	0.24	0.3	0.05
Calc-silicate skarns										
*Glngar GW-1				3.23		489		10		7.31
*Glngar GW-2				3.85		77		<5		2.27
*Glngar SW-2				3.43		94		-5		1.89
*McLar				3.21		1210		55		-1.1
Carbonate-hosted, pyrite-rich										
BAN1FA.1	8	660	41	6.38	7.5	210	0.01	2.1	-0.1	1
LD1FA.1	7	700	155	7.15	7.5	246	1.4	1.2	-0.1	0.05
FG1.1	7	4000		6.23	0.15	1800	3.3	1.4	0.1	*-20*
kok fa	4	820		6.83	0.3	380			0.2	*3*
Carbonate-hosted, pyrite-poor										
Anon1 fa.1	4.5	390		7.42	8				*0.017*	2
Anon2 fa	8	970		7.21	7.5				*0.006*	42
*FishCk1				6.95		17		5		6.5
*Blkwar				7.22		25		7		-1.1
*LilDaisy				7.24		341		6		3.2
Sedimentary-exhalative (SEDEX)										
Hosted by shales and cherts with no carbonates										
*#2016, Alaska (nat.)				4.12		69000	129	354	1900	750
*#2019, Alaska (nat.)				3		11900	30	383	460	205
*#2015, Alaska (nat.)				4.52		7645	14	19	180	65
*#2021, Alaska (nat.)				2.54		2658	4.2	23	190	86
DW010	3	129		4.3		49	0.2	0.1	**1**	*-0.9*
DW017	4	2150		2.8		1180	0.5	-0.4	**53**	*26*
DW018	3	1410		3.1		964	0.55	1	**95**	*4*

Deposit type *Ore / alteration type* Sample	Temp. °C	Spec. Cond. µS/cm	Alk. mg/l $CaCO_3$	pH	Diss. O_2 ppm	SO_4 mg/l	F mg/l	Cl mg/l	Al mg/l	As µg/l
DW024	8	1269		3.1		629	0.5	0.3	**44**	*8*
DW026	8	1242		3.1		610	0.5	0.3	**43**	*7*
RD 23	8.6	195		5.2						
RD33	6.9	192		6.2		75.4				
RD42	6.5	488		3.5						
RD44	3.6	386		5.4						
Hosted by shales, cherts, and carbonates										
LK57	5	127		6.2		127	0.2	0.6	0.2	
LK61	6	190		6.8		26	0.2	0.4	**0.2**	
LK62	5	320		7.6		60	0.3	0.4	**-0.1**	
Mississippi-Valley-Type (MVT)										
Jasperoid-poor										
*Site 4-Drill (mean)	14	946	296	7.1		260		10.6		
*Site 5 (mean)	11	998	240	8		340		15.1		
*Site 8 (mean)	15.4	1199	129	6.7		612		5.7		
DAU1.FA.1	1.5	90		7.86	9.5	2.3	-0.2	0.21	0.01	1
RUB1.RA	5	260		7.84	6	5.1	0.02	0.25	0.027	*5.6*
WP2FA.1	8		207	8.16	10				0.01	0.05
Abundant jasperoid										
*Map # 101	16	1730	53	5.7	0.5	940	0.5	4.9		
*Map #105	16.5	1530	80	7.1	9	830	0.6	3.1		
*Map # 109		2100	126	6.4		1100				
*Map # 14	10.5	386	90	7.3	9	88	0.5	4.3	0.02	
*Map #16	10	234	11	6.7	9.7	79	0.2			
*Map # 17	16.5	1100	69	7.2	8.5	490	0.5	3.6		
Sediment-hosted Au										
Primarily oxide ore										
*Boss 4/1/94			102	8.18		4860	4.3	4310		3100
*Boss Pit 7/1/94			100	8.19		4330	4.3	2740		920
*Boss Pit 12/26/94			102	8.1		4040	4.5	2580		1200
*Cortez East, 6/15/92				8.02		86.5	1.8	24.8		38
*Cortez Middle, 6/15/92			228	8.07		86	1.8	27.8		37
*Cortez West, 6/15/92			225	8.13		81.9	1.8	26.9		40
*Big Springs 5/30/95		1200	127	8.1		646	0.44	-1.5	-0.2	12
*Big Springs 4/13/95		656	80.7	7.75		283	0.15	1.6	-0.2	24
Primarily sulfide ore, carbonate-poor host rocks										
DW-06, 12/22/94	20.6		177	7.6		48.6	0.6	12.5		1180
DW-06, 12/22/94	24		172	7.8		48	0.6	12		680
DW-07,12/22/94	19.4		168	7.6		45.3	0.6	18.3		280
394318-1,6/14/95	17.9		189	7.55		68.3	0.5	15.3		510
394319-2,8/17/95	18		199	7.78		47.7	0.5	13.9		210
Low-sulfide Au-quartz veins										
LCk2	12	85	19	7.8		4.2		2		130
SF6	4	64	40	7.7		5.3		1.4		10
Goy13	8	19	13	7		0.8		0.4		40
McKin2	6	56	22.8	7.2					*0.055*	*9*

Deposit type *Ore / alteration type* Sample	Temp. °C	Spec. Cond. µS/cm	Alk. mg/l $CaCO_3$	pH	Diss. O_2 ppm	SO_4 mg/l	F mg/l	Cl mg/l	Al mg/l	As µg/l
McKin5	8	19	14.8	7.4		3.4		1	*0.014*	*9*
McKin11	8.5	61	34.8	6.6		3.9		1.6	*0.008*	*51*
McKin13	11.5	17	3.6	5.8		1.1		1.1	*0.036*	*4*
McKin19	8	46	18.2	6.4		4		1.9	*0.011*	*94*
Ind1	4	127	34	6.9		32	-0.05	0.12	*-0.01*	*3*
Ind2	2	249	75	7.8		38	0.11	0.27	*-0.01*	*37*
GC4	4	166	48	7.3		18	-0.05	0.12	*-0.01*	*3*
HG6	7	82	27	8.7		6.3	-0.05	0.17	*-0.01*	*5*
HG7	4	66	21	7.5		6.2	-0.05	0.17	*-0.01*	*4*
HY16	9	339	-10	5.2		150	0.17	0.18	*0.19*	*80*
Ch21	3	324	105	7.6		72	0.16	0.29	*-0.01*	*84*
Pt22	5	383	155	7.3		77	0.07	0.29	*0.01*	*14*
Sc23	6	532	250	8.1		91	0.14	0.19	*-0.01*	*92*
M27	11	2350	-10	2.3		1130	0.33	2.2	*7.5*	*-2*
Eb28	7	384	170	8		48	0.33	2.1	*-0.01*	*7*
AJ29	6	897	160	8		349	-0.05	0.53	*-0.01*	*2*
Alkalic Au-Ag-Te veins										
CAR1FA.1	23.5	2800	331	7.66	7.5	1225	3.8	22	0.061	3.4
hur 1 fa	4.5	300	79	7.86	8				**6**	*-2*
swa 1 fa	6	520	160	7.33	7.5				*0.036*	*-2*
Sediment-hosted U										
*MVD-1	14	5950	336	7	0.4	3700	1.8	65		
*MVD-2	15	7200	406	7.1	0.4	4500	0.5	15		
*MVSW-1	15	5440	324	8	6.2	3300	2.6	51		
*3T-529	16	4200	264	7.5		280	1.3	1000		
*JSW-1	10.5	20300	63	9.5	11.2	12000	3.8	310		

Deposit type *Ore /alteration type* Sample	Ca mg/l	Cd µg/l	Ce µg/l	Co µg/l	Cu µg/l	Fe tot mg/l	Fe^{++} mg/l	Mg mg/l	Mn µg/l	Ni µg/l
Volcanogenic massive sulfide (VMS)										
Kuroko-type, hosted by volcanic rocks										
*Rich-90WA103	**183**	**15900**		**1300**	**290000**	**20300**	18100	**821**	**17100**	**660**
*Rich-90WA108	**424**	**43000**		**2200**	**578000**	**55600**	50800	**1380**	**41800**	**2800**
*Rich-90WA109	**330**	**48300**		**15500**	**2340000**	**86200**	79700	**1450**	**42100**	**2900**
*Rich-90WA110A	**279**	**211000**		**5300**	**4760000**	**111000**	34500	**437**	**22900**	**3700**
*LMG	5	45300			191000	29800	16700	2790	146000	
Hol-511	*130*	*5.9*	*27*	*9*	*200*	*270*		*27*	*2100*	*11*
Hol-528	*130*	*22*	*48*	*27*	*330*	*390*		*44*	*2700*	*28*
Hol-529	*84*	*28*	*24*	*25*	*300*	*110*		*28*	*1500*	*23*
Hol-534	*94*	*29*	*2*	*5.6*	*900*	*0.94*		*8.8*	*320*	*7.2*
Hol-548	*78*	*62*	*4.2*	*27*	*3*	*-0.2*		*9.6*	*320*	*78*
Hol-549A	*160*	*1500*	*110*	*510*	*>40000*	*440*		*>100*	*>6000*	*150*
Hol-549B	*130*	*2300*	*170*	*970*	*>40000*	*>500*		*>100*	*>6000*	*180*
Besshi-type, hosted by sedimentary and intermediate submarine volcanic host rocks										
Duch-1	42	0.8		1.8	9.5	0.13		4	200	-6
Duch-2	18	0.9		18	760	7.1		5.7	200	7
Black-18A	10	9.6		30	3600	21		36	750	10
Beat-16	12	-0.7		10	52	4.5		2.9	390	8
V-Ely-1	**42**	**-10**		**210**	**3500**	**17**		**14**	**1300**	**52**
Besshi-type, hosted by graphitic schists										
FC-3	**6.9**	*0.7*	*0.2*	*1.2*	**97**	*0.047*		**2.4**	**150**	*1.0*
SUG-1 0.2	**9.9**	*18*	*54*	*15*	**7200**	**0.55**		**7.1**	**940**	7.4
Cobalt-rich, hosted by metamorphosed sediments										
*BB25	140			150000	78000	0.15		115	14000	
High sulfidation (quartz alunite epithermal)										
Acid sulfate alteration										
AD-3	**80**	**180**	**84**	**670**	**93000**	260		**25**	14	**760**
AD-3	**93**	**200**	**80**	**700**	**120000**	**310**		**34**	**18000**	**800**
AD-3	**120**	**330**	*80*	**1600**	**234000**	**920**		**51**	**31000**	**1900**
AD-3	**110**	**300**	*180*	**950**	**230000**	**570**		**45**	**23000**	**1200**
AD-3	**69**	**72**	*130*	**420**	**70000**	**190**	**177**	**20**	**12000**	**550**
AD-1435C	**48**	**70**	*20*	**540**	**84000**	**250**		**18**	**10000**	**640**
Chand-1	**150**	**440**	*450*	**2000**	**400000**	**1400**	**196**	**87**	**40000**	**2600**
Chand-1	**160**	**380**	*390*	**1400**	**290000**	**910**	**985**	**71**	**34000**	**1800**
Chand-1	**160**	**430**	*380*	**1400**	**260000**	**880**	**760**	**65**	**35000**	**1700**
Dike 2	**360**	**1000**	**2000**	**7000**	**220000**	**5010**		**380**	**180000**	**10000**
550D-R	**220**	**360**	*200*	**3000**	**56000**	**1100**		**150**	**92000**	**3600**
North Dump	**130**	**140**	*70*	**1000**	**39000**	**320**		**46**	**40000**	**1100**
N Dump S Seep	**310**	**400**	*1000*	**2400**	**100000**	**1200**	**635**	**100**	**65000**	**2600**
SC12	**250**	**180**	*150*	**1700**	**100000**	**540**		**58**	**77000**	**1400**
Blackstrap	**380**	**3000**	**6000**	**16000**	**460000**	**27900**		**840**	**370000**	28000
SOB-1 Seep	**480**	**460**	*780*	**7700**	**706000**	**12000**		**190**	**> 100000**	**11000**
IOWA-1	**82**	**81**	*300*	**460**	**19000**	**170**		**29**	**19000**	**580**
SPIT-1 Pond	**15**	**73**	*78*	**670**	**42000**	**470**		**9**	**4200**	**860**
SPIT-2 Pond	**30**	**110**	*220*	**1100**	**120000**	**840**		**23**	**19000**	**1300**
NPIT-1 Pond	**60**	**120**	*200*	**630**	**37000**	**280**	**79**	**29**	**15000**	**830**
Ch Seep	**69**	**220**	*260*	**950**	**270000**	**540**	**338**	**31**	**28000**	**1200**
Missionary East	**59**	**50**	*94*	**260**	**58000**	**150**	**169**	**15**	**5800**	**350**
Sh-1	**560**	**130**	*1100*	**1300**	**32000**	**600**	**223**	**140**	**100000**	**1300**

Deposit type *Ore /alteration type* Sample	Ca mg/l	Cd µg/l	Ce µg/l	Co µg/l	Cu µg/l	Fe tot mg/l	Fe^{++} mg/l	Mg mg/l	Mn µg/l	Ni µg/l
TD Seep	**87**	**7**	*9.3*	**80**	**28000**	**39**	**35**	**13**	**2400**	**82**
AREA L	**77**	**39**	*330*	**440**	**24000**	**390**	**102**	**24**	**14000**	**570**
lkp fa	**100**	**600**	*92*	**230**	**54000**	**420**		**24**	**16000**	**220**
long 1 fa	**66**	**63**	*13*	**63**	**1500**	**120**		**12**	**2400**	*23*
3R-1	**10**	**41**		**67**	**73000**	**0.54**		**6**	**520**	**65**
*EC91AP16	5				120	0		2		
*EC91AP19	4				1	0		2		
*EC91AP22	0				10	0		1		
*EC91AP24	23				320	1		11		
*EC92AP-21	165				150	89		10		
Propylitic alteration										
Missionary West	**73**	*-20*	*-1*	*3*	**150**	*-0.4*	*nm*	**11**	**700**	*-30*
Cordilleran Lode										
Advanced-argillic to quartz-sericite-pyrite alteration										
*Berkeley Pit Surf.	453	1300			6900	250		194	79000	
*Berkeley Pit 3 m	462	1300			156000	386		201	95000	
*Berkeley Pit 100 m	506	1900			218000	1040		272	162000	
Hot Spring S/Au										
Shallow acid-sulfate alteration										
*82WA119	266	338		5070	9640	2510		97	9320	13000
*81WA132C	110	150		3300	1200	1160		42	7600	8000
*82WA118	131	282		5110	5320	1570		53.8	10500	11900
Climax-type Porphyry Mo										
Potassic, quartz-sericite-pyrite, greisen alteration										
mcn 1 fa	**420**	**520**	*800*	**1000**	**16000**	**140**		**260**	**79000**	**1300**
mcn 2 fa	**220**	**290**	*500*	**610**	**8700**	**210**		**110**	**59000**	**770**
Porphyry Cu, Cu/Mo										
Quartz-sericite-pyrite alteration										
*MW Weir 3	31.6			138	16800	9.6		4.4	954	50
*MW Weir 1	156			295	15000	5.6		13	4070	150
*MW BH89-14	5.2			38	3050	1.29		1.3	368	-20
*MW BH89-4	128			483	9050	45.5		19	4760	260
*MW BH89-3	109			370	4200	26.8		14	6770	220
*MW BH89-10	91.1			163	18	53.4		11.2	5000	50
*MW BH89-8	97.8			205	1300	56.2		13.8	8410	40
*MP1W1, Globe	440	600		13000	150000	2800		390	75000	3100
TMT-29	**4.3**	*14.0*		*200*	*1300*	**150**	5	**3**	**130**	*110*
TMT-28	**13.0**	*15.0*		*210*	*65*	**130**	135	**11**	**1700**	*110*
TMT-38	**150.0**	*29.0*		*530*	*2000*	**1900**	1590	**130**	**45000**	*280*
Propylitic alteration										
*MW BH89-2	7.6			-5	91	0.03		1.4	189	-20
*MW BH89-13	105			-5	-5	0.017		24.5	0.75	-20
Algoma Banded Fe Formation										
Sulfide-facies										
*Sherman S Pit					100	10			5000	100

Deposit type *Ore /alteration type* Sample	Ca mg/l	Cd µg/l	Ce µg/l	Co µg/l	Cu µg/l	Fe tot mg/l	Fe^{++} mg/l	Mg mg/l	Mn µg/l	Ni µg/l
Polymetallic veins										
Zn, Pb, ± Cu-rich										
St.Kev	80.7	670		100	600	120		25.5	55600	100
St.Kev	80.2	430		90	500	111		26.7	62900	100
PENN1.1		*180*	*76*	92	5700	34	35			*110*
SHO1.1		*80*	*-10*	*17*	*680*		2			*40*
Au-quartz-pyrite										
DRUID1FA.45	**190**	**840**	*870*	**780**	**44000**	248		**200**	**74000**	**1500**
Druid shaft	**430**	**960**	*510*	**780**	**5700**	**1300**		**170**	**190000**	**2000**
Argo 1 fa	**290**	**170**	*430*	**180**	**6700**	**170**	3000	**110**	**95000**	**280**
Argo 1 fa.1	**280**	**140**	*370*	**150**	**4900**	**150**		**100**	**90000**	**220**
ARGO1.1	**340**	120	250	88	**6400**	99	30	**130**	**101000**	110
VC1A.1		*240*	*81*	*200*	140	72	160		57000	*300*
VC1B.1		*250*	*100*	*240*	260	65	140		62000	*340*
Pyrite-rich; Zn, Pb, Cu-poor										
PMB193 FA .2	**7**	*2*	*6.1*	**120**	**78**	**150**	120	**2**	**310**	**100**
PMB1FA.1	*5.5*	3	*4.4*	120	120	140	200	*1.7*	*470*	110
Burnt Adit	**33**	*1*	*5.6*	*12*	**100**	**5**		**7**	**460**	*-10*
Burnt Dump	**81**	*-1*	*2.3*	*10*	*11*	**-1**		**15**	**220**	*20*
ARC FA .2	**150**	*4.7*	*360*	**240**	**350**	**92**		**100**	**15000**	*150*
Fe Spring, Fe Crk	**7**	*-1*	*2.0*	*33*	*3*	**26**		**2**	**650**	*20*
Burnt Spring	**320**	*2*	*24*	**110**	**58**	**72**		**42**	**4200**	*40*
SMCB1FA.1	**30**	1.1	4.4	25	2	55	100	**9**	**260**	9.6
Carbonate-rich, or in rocks altered to contain carbonate										
CHAP3FA.45	**270**	*1*	*9.8*	*21*	*1*	6.03	5	**8**	**1000**	*8.2*
CHAP2FA.1	**470**	0.3	0.06	7.2	1	2.48	3	**7**	**420**	*15*
bon 1 fa	**83**	6	3	19	36	**14**		**6**	**2400**	*5*
MIZ FA .2	**130**	*-1*	*0.1*	*4.5*	*2.5*	**2**		**13**	**280**	*7.7*
ASIA FA .2	**92**	*-1*	*0.3*	*1.4*	*18*	**4**		**11**	**420**	*4*
CARC-1 FA .2	**100**	*2*	*10*	**70**	*22*	**14**		**29**	**4400**	**39**
CARC-3 FA .2	**64**	*1*	*0.1*	*5.0*	*-2*	**6**		**17**	**1300**	*-10*
CARC-2 FA .2	**75**	*-1*	*0.2*	*8.0*	*-2*	**2**		**11**	**1000**	*-10*
ns1 fa	**130**	*5*	*2.7*	*8*	**170**	**3**		**19**	**3200**	*6*
para up fa	**350**	*-1*	*99*	*33*	*1*	**24**		**16**	**2400**	*11*
Para 1 fa	**390**	*3*	*210*	**120**	**190**	**67**		**35**	**5600**	*18*
BUR FA .2 8/1	**93**	**140**	0.5	8.0	*23*	**-1**		**48**	**2000**	**43**
NATL FA .2 8/	**190**	*3*	*0.3*	**93**	*11*	**35**		**56**	**18000**	**210**
NTUN1.1	**222**	*28*	*4*	**140**	**50**	29		**65**	**21000**	**280**
GAM6FA.1	**54**	0.72	0.03	0.29	2	-0.01	0.01	**14**	**54**	8.1
MC1FA.1	**30**	0.2	0.03	1.3	2	1.74	2.5	**2**	**760**	2
Creede-type epithermal										
Carbonate-poor										
AL1FA.1	**91**	**44**	*27.8*	*30*	**290**	0.42	0.5	**10**	**3700**	*9.8*
SOL1FA.1	**62**	**160**	5.4	**82**	33	0.5	0.8	**17**	**6000**	12
Carbonate-rich, or in propylitically altered rocks										
RAW1FA.1	130	140	9	30	1200	23.3	32	18	24000	36
*Rawley	130	200			670			15	32000	50
*Rawley	130	13			570	5.4		15	29000	48
*Rawley	120	110		70	420	4.3		15	29000	50

Deposit type *Ore /alteration type* Sample	Ca mg/l	Cd µg/l	Ce µg/l	Co µg/l	Cu µg/l	Fe tot mg/l	Fe^{++} mg/l	Mg mg/l	Mn µg/l	Ni µg/l
Raw1 (Rawley 12)	**160**	**280**	*44*	**69**	**4900**	**42.00**	3.2	**22.00**	**38000**	*36*
ML-ad	140	80	*1.2*	*31*	98	19.00		22.00	32000	*23*
ML-FP	76	*4.3*	*0.3*	*18*	*-2*	13.00		10.00	19000	*13*
ML-1	50	350	*180*	44	9800	6.00		11.00	89000	*58*
Rawley 3 seep	**18**	**66**	*36*	*15*	**6400**	**13.00**		**5.00**	**7300**	*12*
KC tail	**420**	**620**	*890*	**470**	**48000**	**890**	900	**78**	**150000**	**240**
Am 1 fa	**400**	**61**	*4*	**58**	**140**	**18**		**14**	**27000**	*20*
Magmatic sulfide										
Massive iron-, nickel-, and copper-sulfide lenses in ultramafic rocks										
*DUL				1200	7300					24500
Polymetallic replacement and skarns										
Sandstones and other carbonate-poor host rocks										
*Eagle 1610	507	250		570	-150	741		840	493000	
*Eagle 1610	435	300			450	670		1030	560000	
*Eagle 1610	460	500		600	700	660		1160	610000	2100
*Eagle Chief		640		-150	1280	56			69000	
*Eagle Chief	270	1060			5500	103		329	190000	
Igneous-hosted ores										
GAM4FA.1	**85**	11	18	**100**	100	4.67	2	**17**	**3000**	38
YAK1FA.1	**91**	**290**	9.2	18	**2400**	2.42	3	**53**	**20000**	31
GAR1FA.1	**21**	12	0.81	1.5	12	-0.01	0.1	**4**	**1600**	4.2
Calc-silicate skarns										
*Glngar GW-1		3		46.1	7730	86			5610	99.2
*Glngar GW-2		3		21.4	121	14			1020	20.5
*Glngar SW-2		3		15.4	1170	3			722	32.5
*McLar		20		133	26700	192			7	141
Carbonate-hosted, pyrite-rich										
BAN1FA.1	**89**	**61**	0.17	38	38	2	1.5	8	7200	17
LD1FA.1	**87**	12	0.03	1	4	0.01	0.2	37	1100	4.3
FG1.1		0.5	*69*	*120*	*270*	86	500			*190*
kok fa	**110**	**44**	*0.2*	*7*	*41*	**15**		**28**	**3800**	*13*
Carbonate-hosted, pyrite-poor										
Anon1 fa.1	**48**	*2*	*-0.1*	*0.9*	*2*	-0.005		**8**	*23*	*2*
Anon2 fa	**99**	*-1*	*-0.1*	*0.6*	*-1*	-0.005	0.1	**34**	*16*	*3*
*FishCk1		-2.6		-9.7	51.1	0.756			91.6	14.8
*Blkwar		-2.6		-9.7	23.4	1.3			65.8	-12.7
*LilDaisy		-2.6		-9.7	96.1	4.15			1460	37.2
Sedimentary-exhalative (SEDEX)										
Hosted by shales and cherts with no carbonates										
*#2016, Alaska	210			30000	900	10000		9800	800000	
*#2019, Alaska	275			5500	620	870		2000	145000	
*#2015, Alaska	250			3100	230	920		1200	80000	
*#2021, Alaska	155			540	4000	170		245	20000	
DW010	**11**	*6*		*6*	*7*	**3**		**1**	**480**	*22*
DW017	**21**	*6*		*48*	*260*	**270**		**5**	**2200**	*290*
DW018	**19**	*5*		*47*	*67*	**150**		**3**	**1100**	*180*
DW024	**19**	*6*		*48*	*140*	**130**		**7**	**2900**	*230*

Deposit type *Ore /alteration type* Sample	Ca mg/l	Cd µg/l	Ce µg/l	Co µg/l	Cu µg/l	Fe tot mg/l	Fe^{++} mg/l	Mg mg/l	Mn µg/l	Ni µg/l
DW026	**19**	*6*		*43*	*130*	**130**		**7**	**2700**	*210*
RD 23	13	78								
RD33	15	79		-7	11	1.3		6.6	106	-5
RD42	35	396								
RD44	54	105								
Hosted by shales, cherts, and carbonates										
LK57	27	5		-3	-10	0.15		4	330	51
LK61	**32**	**-1**		**-3**	**-10**	**-0.05**		**2**	**-1**	**-5**
LK62	**53**	**-1**		**-3**	**-10**	**-0.05**		**6**	**-1**	**-5**
Mississippi-Valley-type (MVT)										
Jasperoid-poor										
*Site 4-Drill (mean)	113	1		26		0.01		63	22	73
*Site 5 (mean)	124	1		37		0.01		65	242	33
*Site 8 (mean)	190	21		460		0.02		64	18	462
DAU1.FA.1	**11**	0.44	0.03	0.2	1	0.001	0.1	**5**	**22**	3
RUB1.RA	**41**	*0.4*	*0.15*	*0.36*	2	0.13	0.1	**14**	**94**	*3*
*WP2FA.1	**58**	*0.76*	*0.02*	*0.33*	*1.1*	-0.01		**28**	**90**	1
Abundant jasperoid										
*Map # 101	290	30		37	2	67		19	800	98
*Map #105	360	31			7	0.17		6.9	100	52
*Map # 109	530	2				17		8	550	
*Map # 14	63	1		2		0.08		3.5	60	7
*Map #16	20	27		4		0.01		0.8	90	11
*Map # 17	230	60		2		0.01		5.5	40	29
Sediment-hosted Au										
Primarily oxide ore										
*Boss 4/1/94	150	-10			190	0.81		66	-50	
*Boss Pit 7/1/94	190	-10			-50	-0.05		110	-50	
*Boss Pit 12/26/94	340	-10			-50	3.2		65	-500	
*Cortez E., 6/15/92	44.2	-7			-7	0.145		18	5	
*Cortez M., 6/15/92	43.1	-7			-7	0.257		17.7	-3	
*Cortez W., 6/15/92	43.1	-7			-7	-0.05		17.7	-3	
*Big Spr. 5/30/95	107	-5			-5	-0.05		130	243	
*Big Spr. 4/13/95	72.9	-5			-5	-0.05		42.6	63	
Primarily sulfide ore, carbonate-poor host rocks										
DW-06, 12/22/94	51.3	-2			-2	0.4		19.3	64	
DW-06, 12/22/94	46	-0.2			-100	0.1		18	-100	
DW-07,12/22/94	50	-2			-2	0.055		20.5	30	
394318-1,6/14/95	55.2	-2			-3	2.74		21.7	102	
394319-2,8/17/95	42.1	-2			-3	-0.017		22	-1	
Low-sulfide Au-quartz veins										
LCk2	15				-1	-0.01		0.3		
SF6	15				-1	-0.01		-0.1		
Goy13	2.9				2	0.02		-0.1		
McKin2	*2*	*-0.7*			*0.6*	*-0.02*		*0.1*		
McKin5	*5.5*	*-0.7*			*0.7*	*-0.02*		*0.35*		
McKin11	*13*	*-0.7*			*0.4*	*0.03*		*0.6*		

Deposit type *Ore /alteration type* Sample	Ca mg/l	Cd µg/l	Ce µg/l	Co µg/l	Cu µg/l	Fe tot mg/l	Fe^{++} mg/l	Mg mg/l	Mn µg/l	Ni µg/l
McKin13	*0.7*	*-0.7*			*0.9*	*0.02*		*0.1*		
McKin19	*6.6*	*1*			*1*	*0.09*		*0.46*		
Ind1	*14*	*2*		*-0.1*	*-2*	*-0.04*		*6.2*	*0.6*	*0.6*
Ind2	*25*	*2*		*0.1*	*-2*	*-0.04*		*9.6*	*0.4*	*1*
GC4	*20*	*2*		*0.1*	*-2*	*-0.04*		*5*	*-0.3*	*1*
HG6	*12*	*2*		*-0.1*	*-2*	*-0.04*		*0.63*	*-0.3*	*0.6*
HG7	*9.3*	*2*		*-0.1*	*-2*	*-0.04*		*0.49*	*-0.3*	*0.6*
HY16	*31*	*20*		*1*	*10*	*0.3*		*13*	*860*	*100*
Ch21	*49*	*3*		*2*	*-2*	*0.1*		*9.4*	*280*	*12*
Pt22	*57*	*2*		*0.2*	*5*	*0.09*		*14*	*8.3*	*5.5*
Sc23	*74*	*2*		*0.2*	*-2*	*-0.04*		*30*	*1.7*	*3.7*
M27	*93*	*32*		*160*	*380*	*330*		*20*	*1800*	*120*
Eb28	*34*	*1*		*0.3*	*2*	*0.2*		*11*	*1.3*	*3.4*
AJ29	*120*	*2*		*0.4*	*-2*	*0.04*		*37*	*0.8*	*10*
Alkalic Au-Ag-Te veins										
CAR1FA.1	**490**	1	0.11	4	1	0.03	0.2	**36**	**1100**	19
hur 1 fa	**42**	*2*	*3*	*3.5*	**75**	0.5	0.8	**9**	**500**	*3*
swa 1 fa	**66**	*-1*	*0.7*	*4.3*	2	**2**	1.5	**16**	**500**	*4*
Sediment-hosted U										
*MVD-1	440	4		1700	40	1.9		540	2700	850
*MVD-2	430	4		1100	200	0.24		640	1700	540
*MVSW-1	430	-3		9	-30	0.028		430	65	30
*3T-529	82	-3		-9	-30	0.73		31	250	-30
*JSW-1	620	2		-4	-10	0.043		130	-10	-1

Deposit type *Ore / alteration type* Sample	Pb µg/l	Si mg/l	U µg/l	Zn µg/l	Zn+Cu+Cd+ Co+Ni+Pb µg/l
Volcanogenic massive sulfide (VMS)					
Kuroko-type, hosted by volcanic rocks					
*Rich-90WA103	**3600**			**2010000**	2321460
*Rich-90WA108	**4300**			**6150000**	6780300
*Rich-90WA109	**3800**			**7650000**	10060500
*Rich-90WA110A	**11900**			**23500000**	28491900
*LMG	1800			13800000	14038100
Hol-511	*-0.3*		*3.2*	*1000*	1226
Hol-528	*-0.3*		*2.9*	*6000*	6407
Hol-529	*-0.3*		*2.2*	*4800*	5176
Hol-534	*22*		*2.5*	*6000*	6964
Hol-548	*0.6*		*0.7*	*6500*	6671
Hol-549A	*26*		*210*	*81000*	83246
Hol-549B	*23*		*600*	*140000*	143533
Besshi-type, hosted by sedimentary and intermediate submarine volcanic host rocks					
Duch-1	0.9			180	194
Duch-2	74			200	1060
Black-18A	220			3300	7170
Beat-16	-0.5			190	260
V-Ely-1	**-50**	**24**		**1100**	4868
Besshi-type, hosted by graphitic schists					
FC-3	*-0.6*	**5.8**	*-0.1*	**350**	450
SUG-1 0.2	**230**	**7.4**	*0.6*	**7400**	14870
Cobalt-rich, hosted by metamorphosed sediments					
*BB25			0.1	700000	928000
High sulfidation (quartz alunite epithermal)					
Acid sulfate alteration					
AD-3	**370**	**30**	31	**18000**	112980
AD-3	*320*	**31**	*410*	**20000**	142020
AD-3	**230**	**30**	*140*	**47000**	285060
AD-3	*320*	**32**	*38*	**31000**	263770
AD-3	*75*	**27**	*15*	**12000**	83117
AD-1435C	**92**	**28**	*40*	**11000**	96342
Chand-1	***220***	**37**	*170*	**57000**	462260
Chand-1	*310*	**39**	*170*	**47000**	340890
Chand-1	*220*	**42**	*100*	**49000**	312750
Dike 2	**12**	**83**	1000	**170000**	408012
550D-R	*0.2*	**43**	*310*	**61000**	123960
North Dump	*6.3*	**30**	*60*	**23000**	64246
N Dump S Seep	*0.4*	**60**	*210*	**55000**	160400
SC12	*5*	**27**	*60*	**28000**	131285
Blackstrap	*-200*	**84**	*36000*	**610000**	1117020
SOB-1 Seep	*-2*	**110**	*300*	**82000**	807160
IOWA-1	*-0.1*	**35**	*44*	**11000**	31121
SPIT-1 Pond	*0.1*	**1**	*42*	**11000**	54603
SPIT-2 Pond	*1.0*	**1**	*90*	**20000**	142511
NPIT-1 Pond	*1.3*	**11**	*150*	**15000**	53581
Ch Seep	*180*	**27**	*72*	**29000**	301550
Missionary East	*210*	**19**	*29*	**6800**	65670

Deposit type *Ore / alteration type* Sample	Pb µg/l	Si mg/l	U µg/l	Zn µg/l	Zn+Cu+Cd+ Co+Ni+Pb µg/l
Sh-1	*-2*	**36**	*39*	**21000**	55730
TD Seep	*27*	**12**	*0.3*	**2300**	30496
AREA L	*0.6*	**15**	*72*	**6600**	31650
lkp fa	*150*	**16**	*61*	**170000**	225200
long 1 fa	**800**	**8**	*7*	**13000**	15449
3R-1	**-50**	**44**		**580**	73758
*EC91AP16	20	7		10	150
*EC91AP19	10	9		10	21
*EC91AP22	20	9		10	40
*EC91AP24	50	21		40	410
*EC92AP-21	110	37		650	910
Propylitic alteration					
Missionary West	*-2*	**12**	*-1*	**190**	348
Cordilleran Lode					
Advanced-argillic to quartz-sericite-pyrite alteration					
*Berkeley Pit Surface				184000	192200
*Berkeley Pit 3 meters				280000	437300
*Berkeley Pit 100 meters				496000	715900
Hot Spring S/Au					
Shallow acid-sulfate alteration					
*82WA119	38			2620	30706
*81WA132C	-20			1400	14052
*82WA118	75			1390	24077
Climax-type Porphyry Mo					
Potassic, quartz-sericite-pyrite, greisen alteration					
mcn 1 fa	*2.4*	**27**	*8400*	**43000**	61822
mcn 2 fa	*-0.3*	**23**	*5500*	**24000**	34370
Porphyry Cu, Cu/Mo					
Quartz-sericite-pyrite alteration					
*MW Weir 3		7.07		346	17334
*MW Weir 1		13.5		738	16183
*MW BH89-14		3.02		109	3199
*MW BH89-4		14		1650	11443
*MW BH89-3		15.8		1120	5910
*MW BH89-10		11.9		181	412
*MW BH89-8		9.7		106	1651
*MP1W1, Globe	210			22000	188910
TMT-29	*0.03*	**38**		**420**	2044
TMT-28	*0.04*	**41**		**610**	1010
TMT-38	*26*	**39**		**2700**	5565
Propylitic alteration					
*MW BH89-2		2.54		22	116
*MW BH89-13		5.3		-2	3

Deposit type *Ore / alteration type* Sample	Pb µg/l	Si mg/l	U µg/l	Zn µg/l	Zn+Cu+Cd+ Co+Ni+Pb µg/l
Algoma Banded Fe Formation					
Sulfide-facies					
*Sherman S Pit				160	360
Polymetallic veins					
Zn, Pb, ± Cu-rich					
St.Kev	9	22.9		117	1596
St.Kev	10	22.9		99.6	1230
PENN1.1	*50*		*16*	32000	38132
SHO1.1	*260*		*6.4*	1800	2877
Au-quartz-pyrite					
DRUID1FA.45	*15*	**65**	*1400*	**>100000**	167135
Druid shaft	*68*	**45**	*460*	**160000**	169508
Argo 1 fa	*55*	**23**	*100*	**51000**	58385
Argo 1 fa.1	*34*	**19**	*64*	**45000**	50444
ARGO1.1	*42*	9.7	**-100**	**54000**	60760
VC1A.1	*-20*		*16*	53000	53882
VC1B.1	*40*		*22*	55000	56130
Pyrite-rich; Zn, Pb, Cu-poor					
PMB193 FA .2	*0.2*	**33**	*1.4*	**180**	480
PMB1FA.1	1	>2	*1.6*	210	564
Burnt Adit	*0.4*	**14**	*0.8*	**58**	172
Burnt Dump	*0.5*	**14**	*-0.1*	**67**	109
ARC FA .2	*-0.1*	**22**	*15*	**930**	1675
Fe Spring, Fe Crk	*1.0*	**11**	*0.5*	**130**	187
Burnt Spring	*1.3*	**21**	*0.9*	**810**	1021
SMCB1FA.1	0.6	**36**	1	**170**	208
Carbonate-rich, or in rocks altered to contain carbonate					
CHAP3FA.45	*-0.6*	**15**	*0.88*	**560**	591
CHAP2FA.1	0.6	**14**	0.5	**45**	69
bon 1 fa	*20*	**21**	*0.2*	**1700**	1786
MIZ FA .2	*0.1*	**5**	*2.1*	**41**	56
ASIA FA .2	*0.1*	**7**	*0.2*	**-40**	28
CARC-1 FA .2	*7.4*	**14**	*0.5*	**220**	360
CARC-3 FA .2	*0.6*	**5**	*0.8*	**1200**	1208
CARC-2 FA .2	*1.2*	**5**	*-0.1*	**170**	181
ns1 fa	*-0.3*	**7**	*54*	**1100**	1289
para up fa	*-0.3*	**9**	*-2*	**120**	165
Para 1 fa	*0.4*	**11**	*0.5*	**1200**	1531
BUR FA .2 8/1	*4.5*	**3**	*18*	**68000**	68219
NATL FA .2 8/	*0.3*	**17**	*1.4*	**5500**	5817
NTUN1.1	9		*-1*	**8100**	8607
GAM6FA.1	0.6	**11**	0.08	**230**	242
MC1FA.1	0.6	**11**	0.015	**140**	146
Creede-type epithermal					
Carbonate-poor					
AL1FA.1	0.8	**18**	0.54	**5600**	5975
SOL1FA.1	**1100**	**16**	24	**26000**	27387

Deposit type *Ore / alteration type* Sample	Pb µg/l	Si mg/l	U µg/l	Zn µg/l	Zn+Cu+Cd+Co+Ni+Pb µg/l
Carbonate-rich, or in propylitically altered rocks					
RAW1FA.1	5.4	8	0.68	34000	35411
*Rawley	32			34000	34952
*Rawley	26			32000	32657
*Rawley	18			28000	28668
Raw1 (Rawley 12)	**120**	**10**	*1.6*	**58000**	63405
ML-ad	*4*	**11**	*0.6*	**11000**	11236
ML-FP	*-0.6*	**10**	*-0.1*	**4300**	4336
ML-1	*0.6*	**25**	*9.8*	**67000**	77253
Rawley 3 seep	**120**	**10**	*3.6*	**16000**	22613
KC tail	**1000**	**3**	*100*	**170000**	220330
Am 1 fa	*-0.3*	**8**	*29*	**18000**	18279
Magmatic sulfide					
Massive iron-, nickel-, and copper-sulfide lenses in ultramafic rocks					
*DUL				1400	34400
Polymetallic replacement and skarns					
Sandstones and other carbonate-poor host rocks					
*Eagle 1610	-1250			932000	932960
*Eagle 1610	330	5		1020000	1021080
*Eagle 1610	-625	-13		980000	983963
*Eagle Chief	-1250			175000	177060
*Eagle Chief	230	5		430000	436790
Igneous-hosted ores					
GAM4FA.1	13	**18**	31	**2500**	2762
YAK1FA.1	13	**8**	9	**69000**	71752
GAR1FA.1	4.7	**5**	0.1	**1500**	1534
Calc-silicate skarns					
*Glngar GW-1	40.1			671	8589
*Glngar GW-2	2.5			127	295
*Glngar SW-2	8.2			137	1366
*McLar	6.5			3000	30001
Carbonate-hosted, pyrite-rich					
BAN1FA.1	0.6	**6**	0.14	**14000**	14155
LD1FA.1	0.6	**5**	3.5	**3100**	3122
FG1.1	*150*		*-1*	170000	170731
kok fa	*-0.3*	**3**	12	**27000**	27105
Carbonate-hosted, pyrite-poor					
Anon1 fa.1	*-0.3*	**8**	*2.1*	**710**	717
Anon2 fa	-0.3	7	9.2	27	31
*FishCk1	38.1			64	169
*Blkwar	89.8			430	546
*LilDaisy	526			167	828
Sedimentary-exhalative (SEDEX)					
Hosted by shales and cherts with no carbonates					
*#2016, Alaska (natural)			-0.1	500000	530900
*#2019, Alaska (natural)			20	84000	90120
*#2015, Alaska (natural)			12	49000	52330
*#2021, Alaska (natural)			52	35000	39540

Deposit type *Ore / alteration type* Sample	Pb µg/l	Si mg/l	U µg/l	Zn µg/l	Zn+Cu+Cd+ Co+Ni+Pb µg/l
DW010	*5*	**-1**		*1400*	1446
DW017	*9*	**2**		*2000*	2613
DW018	*10*	**2**		*1900*	2209
DW024	*4*	**2**		*2000*	2428
DW026	*4*	**2**		*1900*	2293
RD 23	554			23700	24332
RD33	132	4		7480	7703
RD42	2100			40000	42496
RD44	1260			8900	10265
Hosted by shales, cherts, and carbonates					
LK57	-10	8		2000	2058
LK61	**-10**	**1**		**14**	17
LK62	**-10**	**1**		**780**	783
Mississippi-Valley-Type (MVT)					
Jasperoid-poor					
*Site 4-Drill (mean)	23	9.7		243	366
*Site 5 (mean)		6.2		346	417
*Site 8 (mean)	51	5.4		15000	15994
DAU1.FA.1	1	**1**	0.62	**55**	61
RUB1.RA	*1*	**1**	1.8	**350**	357
WP2FA.1	*2.2*	**3**	*4.4*	**140**	145
Abundant jasperoid					
*Map # 101	28	23		6300	6495
*Map #105	4	13		17000	17094
*Map # 109	11			12000	12013
*Map # 14		7.6		540	550
*Map #16	450	11		24000	24492
*Map # 17	120	7.4		18000	18211
Sediment-hosted Au					
Primarily oxide ore					
*Boss 4/1/94	90			-50	190
*Boss Pit 7/1/94	-50			-50	
*Boss Pit 12/26/94	-50			-50	
*Cortez East, 6/15/92	-5			-5	
*Cortez Middle, 6/15/92	6			-5	
*Cortez West, 6/15/92	7			6	
*Big Springs 5/30/95	-5			76	
*Big Springs 4/13/95	-5			6	
Primarily sulfide ore, carbonate-poor host rocks					
DW-06, 12/22/94	-40			11	11
DW-06, 12/22/94	-2			-100	
DW-07,12/22/94	-40			-4	
394318-1,6/14/95	-40			-2	
394319-2,8/17/95	-1			10	10

Deposit type *Ore / alteration type* Sample	Pb µg/l	Si mg/l	U µg/l	Zn µg/l	Zn+Cu+Cd+ Co+Ni+Pb µg/l
Low-sulfide Au-quartz veins					
LCk2	-1			6	6
SF6	-1			5	5
Goy13	1			8	11
McKin2	*-0.5*			*4*	5
McKin5	*-0.5*			*3*	4
McKin11	*-0.5*			*4*	5
McKin13	*-0.5*			*5*	6
McKin19	*-0.5*			*8*	10
Ind1	*-0.6*			*-2*	3
Ind2	*-0.6*			*3*	6
GC4	*-0.6*			*-2*	4
HG6	*-0.6*			*-2*	3
HG7	*-0.6*			*-2*	3
HY16	*4.8*			*2000*	2136
Ch21	*-0.6*			*1500*	1517
Pt22	*-0.6*			*2*	15
Sc23	*-0.6*			*-2*	6
M27	*21*			*2500*	3213
Eb28	*-0.6*			*6*	13
AJ29	*-0.6*			*44*	57
Alkalic Au-Ag-Te veins					
CAR1FA.1	0.6	**30**	16	**57**	83
hur 1 fa	*-0.3*	**5**	*37*	**290**	374
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*MVSW-1	-30	0.03		34	79
*3T-529	40	3.8		110	157
*JSW-1	-1	0.7	6	44	48

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Volume 6A

THE ENVIRONMENTAL GEOCHEMISTRY OF MINERAL DEPOSITS
Part A: Processes, Techniques, and Health Issues

Volume Editors: Geoffrey S. Plumlee and Mark J. Logsdon

CONTENTS

INTRODUCTION

PROCESSES

TECHNIQUES

HEALTH ISSUES

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