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Preliminary compilation of descriptive geoenvironmental mineral deposit models

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GEOENVIRONMENTAL MODELS OF MINERAL DEPOSITS-- FUNDAMENTALS AND APPLICATIONS

by Geoffrey S. Plumlee and J. Thomas Nash

INTRODUCTION

Economic geologists recognize that mineral deposits can readily be classified according to similarities in their geologic characteristics (ore and gangue mineralogy, major- and trace-element geochemistry, host rock lithology, wall-rock alteration, physical aspects of ore, etc.), as well as their geologic setting (see for example, Guilbert and Park, 1986). Early geology-based classification schemes have evolved into mineral deposit models that classify deposits not only on the basis of geologic characteristics, but also on the basis of geophysical and geochemical characteristics and the genetic processes by which the deposits form (Cox and Singer, 1986; Bliss, 1992). These conceptual mineral deposit models form the basis for most modern mineral exploration methodologies, and have also been used as tools to help assess the potential for undiscovered mineral resources in regions with known geologic characteristics.

A next step in the process of mineral deposit modeling is development of geology-based, geoenvironmental models for diverse mineral deposit types. Mineral deposit geology, as well as geochemical and biogeochemical processes, fundamentally control the environmental conditions that exist in naturally mineralized areas prior to mining, and conditions that result from mining and mineral processing. Other important natural controls, such as climate, and anthropogenic factors (including mining and mineral processing methods) mostly modify the environmental effects controlled by mineral deposit geology and geochemical processes. Thus, deposits of a given type that have similar geologic characteristics should also have similar environmental signatures that can be quantified by pertinent field and laboratory data and summarized in a geoenvironmental model for that deposit type. Similarly, environmentally important geologic characteristics, such as the presence of an alteration type likely to produce highly acidic drainage water or an alteration type likely to help buffer acid drainage water, should also be common to most or all deposits of a given type, and thus can also be summarized in a geoenvironmental model. As discussed below, the need for and use of geoenvironmental models are immediate and varied; these range from environmental prediction and mitigation, and baseline characterization, to grass-roots mineral exploration, and assessment of abandoned mine lands and mine-site remediation.

This compilation presents preliminary geoenvironmental models for 32 mineral deposit types (or groups thereof) compiled by U.S. Geological Survey earth scientists and environmental geochemists using data available as of mid 1995. The geoenvironmental models follow the classification scheme of, and are numbered according to, the mineral deposit models presented by Cox and Singer (1986) and (Bliss, 1992), to which the reader is referred for additional information concerning the mineral deposit models. This first iteration of geoenvironmental model development has resulted primarily in descriptive summaries of environmentally important geologic characteristics for a variety of mineral deposit types; however, empirical data are included in some models. The models summarized herein should be considered as descriptive guides concerning potential environmental impact, not numeric tools applicable to quantitative risk assessment. Nonetheless, the models provide a basis for understanding and interpreting environmental processes related to mineral deposits in a systematic geologic context. An important goal of future investigations will be to integrate additional empirical data or environmental signatures for diverse deposit types so that the models become more quantitative and can be applied to predict environmental mitigation expenses and risks associated with mineral extraction.

The purpose of this introductory chapter is to present the geologic basis for geoenvironmental models, discuss fundamental components of the models, and describe their uses. Individual models assume that the reader has some knowledge of the terms and concepts of economic geology, geology, and environmental geochemistry; however, this introductory chapter is designed to provide sufficient references, terminology, and basic concepts that readers lacking detailed training in these topics can, with some background work, begin to use the models for a variety of purposes. As a result, this compilation should prove useful to a wide audience, including exploration and economic geologists, environmental scientists, land managers, regulators and others.

GENERAL DEFINITIONS

Economic geology terms

"Mineral deposits", as defined by Cox and Singer (1986), are occurrences of a valuable commodity (such as gold or copper) or mineral (such as gems or industrial minerals) that are of sufficient size and concentration (grade) that

they might, under the most favorable circumstances, be considered to have potential for economic exploitation. An "ore deposit" is a mineral deposit that has been tested and discovered to be of sufficient size, grade, and accessibility to allow it to be extracted at a profit. To slightly modify the definition provided by Cox and Singer (1986), a "mineral deposit model" is a systematic summary of information concerning the geologic characteristics, grade, size, and genesis of a class of similar mineral deposits; the model can be empirical (based on observations or measured data) and (or) theoretical (based on conceptual ideas concerning deposit genesis).

The terminology used to describe geologic characteristics of mineral deposits is far too extensive and diverse to present in this report; interested individuals requiring additional background information are referred to standard economic geology texts, such as Guilbert and Park (1986) and references contained therein, for a complete discussion of terminology.

Environmental terms

The "environmental signatures" or "environmental behavior" of mineral deposits are both defined here to be the suites, concentrations, residences, and availabilities of chemical elements in soil, sediment, airborne particulates, and water at a site that result from the natural weathering of mineral deposits and from mining, mineral processing, and smelting. For example, the environmental signature of a mine site may include metal contents and suites in mine-drainage water, stream sediment, and soil; surface water pH; and identification of readily soluble secondary salts associated with mine waste. The "environmental effects" of mineral deposits are considered to be spatially broader than environmental signatures, in that they include the influence of a site on the surrounding environment, including, for example, the environmental effects of a mine drainage on a river into which the drainage flows.

CONTROLS ON THE ENVIRONMENTAL BEHAVIOR OF MINERAL DEPOSITS

As previously mentioned, the primary tenet of geoenvironmental models is that mineral-deposit geology, along with geochemical and biogeochemical processes, are fundamental controls on the environmental behavior of mineral deposits. Thus, some discussion of geologic controls and other generally subordinate controls, such as climate and mining and milling methods, on environmental signatures is necessary before details of the models can be presented.

Geologic controls

For a detailed discussion, the reader is referred to papers or volumes such as Kwong (1993), Alpers and Blowes (1994), Jambor and Blowes (1994), and Plumlee (in press).

Ore and gangue mineralogy, host rock lithology, and wall-rock alteration: Geologic factors, including mineralogy, host rocks, and wall-rock alteration, all influence the chemical response of mineral deposits and mineral processing by-products on environmental signatures. Many sulfide minerals, including pyrite and marcasite (FeS_2), pyrrhotite (Fe_{1-x}S), chalcopyrite (CuFeS_2), and enargite (Cu_3AsS_4), generate acid when they interact with oxygenated water. Other sulfide minerals, such as sphalerite (ZnS) and galena (PbS) generally do not produce acid when oxygen is the oxidant. However, aqueous ferric iron, which is a by-product of iron sulfide oxidation, is a very aggressive oxidant that, when it reacts with sulfide minerals, generates significantly greater quantities of acid than those generated by oxygen-driven oxidation alone. Thus, the amount of iron sulfide present in a mineralized assemblage plays a crucial role in determining whether acid will be generated (Kwong, 1993; Plumlee, in press). In general, sulfide-rich mineral assemblages with high percentages of iron sulfide or sulfide minerals having iron as a constituent (such as chalcopyrite or iron-rich sphalerite) will generate significantly more acidic water than sphalerite- and galena-rich assemblages that lack iron sulfide minerals. Some non-sulfide minerals such as siderite and alunite can also generate acid during weathering if released iron or aluminum precipitate as hydrous oxide minerals. In contrast to acid-generating sulfide minerals, carbonate minerals, whether present in ore or in host rocks, can help consume acid generated by sulfide oxidation. Other materials that may react with acid, though less readily than carbonate minerals, include aluminosilicate glasses or devitrified glasses (as in volcanic rocks) and magnesium-rich silicate minerals such as olivine and serpentine.

In the case of some industrial minerals such as fibrous silicate minerals, mineralogy plays a well-known, key role in determining adverse health effects associated with intake of these minerals (Ross, in press). For example, chrysotile asbestos, the most common form of asbestos used in industrial applications in the United States, apparently has negligible effects on human cancer incidence, whereas crocidolite and amosite asbestos varieties are clearly linked to greatly increased human mortality rates from certain types of cancer.

Major- and trace-element composition: The major- and trace-element composition of mineral deposits and their host rocks strongly influence the suites of elements dispersed into the environment from given deposit types. Major-element compositions (of iron, aluminum, carbon, etc.) influence, for example, types of precipitates formed in drainage water and can therefore influence trace metal transport mechanisms such as complexing. Metal and trace element suites in ore are commonly reflected in environmental signatures of soil, water, and smelter emissions; for example, most copper-rich ore produces drainage water and smelter emissions with copper as the dominant trace element.

Mineral resistance to weathering and oxidation: The relative rates at which minerals weather play a crucial role in environmental processes, including acid-drainage generation and release of metals into the environment from solid mine or mineral processing wastes. Although the relative weathering rates of various sulfide minerals, as determined in the laboratory, vary considerably from study to study (Jambor and Blowes, 1994; Smith and others, 1994), a general sequence of "weatherability" has been established (listed here in order of decreasing reactivity): pyrrhotite (Fe_{1-x}S) > chalcocite (Cu_2S) > galena (PbS) > sphalerite (ZnS) > pyrite (FeS_2) > enargite (Cu_3AsS_4) > marcasite (FeS_2) > cinnabar (HgS) > molybdenite (MoS_2). As is well known to most field geologists, carbonate minerals are the most reactive of the acid-consuming minerals; of these, calcium carbonate minerals (calcite, aragonite) react most readily with acidic water, whereas iron, magnesium, or manganese carbonate minerals (dolomite, magnesite, siderite) tend to be the least reactive with acidic water. Aluminosilicate minerals tend to react much more weakly with acid water than carbonate minerals; volcanic glass, devitrified volcanic glass, and Fe-, Mg-silicate minerals (such as olivine and serpentine) are the most reactive of the aluminosilicate minerals, whereas feldspars and quartz are the least reactive.

Mineral textures and trace element contents: The rates at which mineral deposits are weathered and oxidized are also influenced by the textures and trace element contents of contained minerals. For example, sulfide crystals that are fine-grained, have massive or fibrous textures, or have high trace element contents typically weather more rapidly than coarse, euhedral, and trace element-poor crystals (Kwong, 1993; Plumlee and others, 1993).

Extent of pre-mining oxidation: As weathering and erosion expose sulfide-bearing mineral deposits, associated potential environmental impact may be reduced as a consequence of sulfide mineral oxidation; some metals contained therein may be subsequently incorporated in relatively less soluble minerals from which metal mobility is limited. These less soluble minerals include hydroxides of iron (such as goethite and limonite), manganese, aluminum, and other metals; some sulfate minerals, such as anglesite, jarosite, plumbojarosite, and alunite; carbonate minerals such as smithsonite, malachite and azurite; and phosphate minerals such as turquoise and hinsdalite. The extent and mineralogic products of pre-mining oxidation are a complex function of deposit geology, hydrology, topography, and climate (see Guilbert and Park, 1986, and references contained therein). For example, along highly permeable veins or alteration zones, sulfide minerals may be oxidized to great depths, whereas sulfide minerals immediately adjacent to low permeability rocks (such as clay altered rocks) may remain unoxidized to within several meters of the ground surface. In regions with steep topography, elevated mechanical erosion rates can greatly exceed chemical weathering rates such that fresh sulfide minerals in highly altered rocks are continually exposed. As another example, a combination of deep paleowater tables and uplift of mountain blocks in the Great Basin during Tertiary time tended to create deeply oxidized ore deposits. Associated ore was easily mined and milled in the 19th Century; today, waste dumps at these mines pose relatively few problems because potentially hazardous elements are tightly held in iron oxide minerals. Many current exploration targets in the pediment areas of the Great Basin are oxidized to relatively great depths. In contrast, areas characterized by widespread mechanical erosion, including terranes that are tectonically active or have been glaciated, tend to have thin weathered zones that may contain sulfide minerals at or near the surface. Mechanical erosion can enhance natural generation of acidic conditions if the climate is semi-arid to humid.

Secondary mineralogy: In contrast to secondary minerals formed by pre-mining mineral deposit weathering, many secondary minerals formed from weathered, sulfide-bearing ore and tailings wastes are quite soluble and can play an important role in controlling metal mobility from mine sites. Of these secondary minerals, the most common and environmentally important are metal sulfate salts of calcium (gypsum), iron (jarosite, melanterite, copiapite, rhomboclase, and many others), copper (chalcantite, brochantite, and others), zinc (goslarite), magnesium (pickeringite), and other metals. These salts form efflorescent coatings on rocks, fractures, and mine workings, and

are produced by evaporation of sulfate-rich drainage water during dry periods or in areas sheltered from water runoff. The salts have variable compositions, and serve as solid storage reservoirs for both metals and acid. Due to their high solubilities, the salts dissolve rapidly during rainstorms or snowmelt; metals and acid released by salt dissolution can lead to temporary but significant degradation of surface- and ground-water quality. Water remaining after storm or snowmelt events can itself become a highly reactive fluid that enhances sulfide mineral oxidation; eventually, these fluids evaporate completely and reinitiate the salt precipitation-dissolution cycle. The particular secondary salts formed depend strongly upon deposit geology, climate, and the extent of evaporation.

Structural and physical characteristics of mineral deposits: The access of weathering agents such ground water and atmospheric oxygen are controlled by the structural and physical characteristics of mineral deposits. For example, veins, sulfide-mineral-rich lenses, or faults can focus groundwater flow, thereby promoting water access to sulfide-rich material and inhibiting contact with potential acid-buffering agents in wall rocks. As another example, zones of intense clay alteration have low permeability and inhibit ground-water flow; consequently, sulfide minerals within clay altered rock can remain unoxidized, even when they are well above the water table.

Climate

Climate affects the environmental behavior of mineral deposits, but its effects are often subordinate to those of deposit geology. Amounts of precipitation and prevailing temperatures influence the amount of water available as surface runoff, the level of the water table, rates of reaction, amounts of organic material, and other parameters that affect weathering of mineralized rocks and ore. In general, water tables are shallow in wet climates and deep in semi-arid climates. However, depths to the water table can be highly variable across short distances within a mining district. Some mining districts in Nevada today have water tables that vary from 0 to 350 m depths within a few kilometers. Deep weathering (oxidation) profiles tend to develop in semi-arid climates. Leaching of elements tends to be intense in humid tropical climates and modest in arid deserts. In humid to semi-arid climates, leaching and transport tends to be downward, whereas in arid climates upward movement of water by capillary action becomes a significant process. Environmental signatures associated with mineral deposits may vary somewhat on a local scale due to microclimate variations, such as exist where mountainous areas with seasonal snow and rain are adjacent to arid valleys in which evaporation exceeds annual precipitation (for example, Nevada and Arizona).

As described below, mine-drainage water associated with sulfide-mineral-bearing deposit types, which generate acid mine water, tends to have lower pH and higher metal contents in dry climates than in wet climates due to evaporative concentration of acid and metals. However, dry-climate mine drainage water with low pH and high metal content may have less environmental impact than a similar deposit in a wet climate setting because of the relatively small volume of surface drainage water. Evaporative processes can also operate in wet climate settings characterized by seasonal wet and dry periods. Relative shifts in pH and metal content for a given deposit type in different climate settings are still very much less than shifts due to differences in geologic characteristics, however.

Very cold climate can have several consequences for environmental processes. First, weathering rates decrease substantially in very cold climates; unweathered sulfide minerals may be abundant at the surface where climate favors permafrost formation. However, during short summer seasons in areas dominated by cold climate, weathering of exposed sulfide minerals can lead to formation of highly acidic water (again depending upon the mineral-deposit geology). Freeze-concentration of acid water can also lead to increased acidity and metal contents.

Climate effects on environmental impact downstream from mineral deposits can be significant. For example, downstream dilution (and therefore environmental mitigation) of acid mine water by dilute water draining unmineralized areas is much more efficient in wet climates than in dry climates. In contrast, downstream mitigation is enhanced in dry climate settings by the increased buffering offered by solid material in stream beds.

The major effects of climate are perhaps best known from world studies of soil (FitzPatrick, 1980) and studies of supergene enrichment of ore deposits (see Guilbert and Park, 1986 and references cited therein), but systematic studies of environmental geochemistry as a function of climate are in their infancy. In detail, the subject is complex, but some generalizations can be made by considering element mobility, deposition, and adsorption in soil and ore deposit supergene zones (Rose and others, 1979; Anderson, 1982).

Mining and mineral processing method

A wide variety of mining and mineral processing methods are currently in use; even more have been used over the course of historic mineral extraction activities. Ultimately, mining and mineral processing methods used to exploit a deposit are strongly dependent on the geologic and mineralogic characteristics of the ore. As with climate, the

effects of mining and mineral processing method on most environmental signatures are generally subordinate to those of mineral-deposit geology. In most cases, abundances of acid and metals in mine water draining deposits with similar geologic characteristics progressively increase from water draining underground workings, to that draining mine dumps, to that draining mill tailings, and finally, to that collecting in open pits. This trend reflects increasing access to weathering agents (water and atmospheric oxygen), increased surface area of sulfide minerals exposed to weathering, and increased opportunities for evaporative concentration. In addition, the size of particles produced by milling and beneficiation processes can dramatically influence the extent of environmental impact. Finely milled ore and tailings, which enhance metal adsorption while enhancing sulfide oxidation, can more rapidly generate acid and are more likely to be distributed by wind and water than their more coarse-grained equivalents.

One important way in which mineral processing techniques are of primary importance relates to techniques that introduce potentially problematic chemicals. For example, mercury amalgamation was widely used as a gold extraction technique in the United States in the last century. As a result, soil and sediment may be mercury contaminated at many sites where amalgamation was practiced historically, but would not otherwise be characterized by elevated mercury abundances.

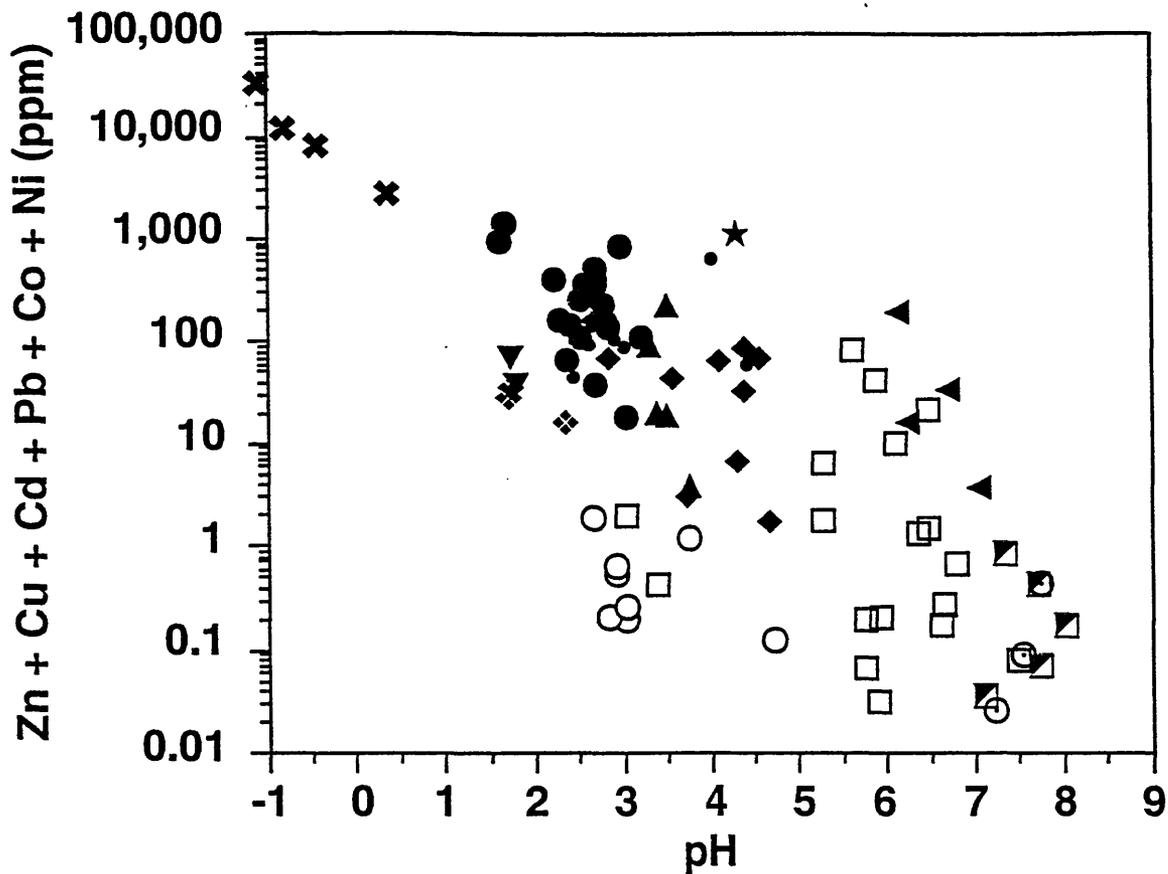
EMPIRICAL STUDY OF GEOLOGIC AND GEOCHEMICAL CONTROLS ON MINE-DRAINAGE COMPOSITION

An ongoing study of mine water that drains a number of different mineral deposits (Plumlee and others, 1993; Smith and others, 1994; fig. 1) illustrates that environmental signatures are a readily predictable function of mineral deposit geology, geochemical processes, climate, and mining method. The importance of geologic controls are also seen in other environmental signatures such as tailings water, cyanide processing solutions, mine wastes, etc. Mine-drainage data from diverse sites in Colorado and elsewhere are grouped (fig. 1) according to the geologic characteristics of the mines drained. In general, the trend of increasing metal content and decreasing pH reflects greater amounts of pyrite and other sulfide minerals, coupled with lesser amounts of acid-buffering minerals associated with the deposits. For example, pyrite- and enargite (Cu_3AsS_4)-rich ore in acid-altered wall rock (such as at Summitville, Colo. and Butte, Mont.) has extreme acid-generating capacity; however, any acid consuming capacity in the host rocks was destroyed by reactions with acidic magmatic gas condensates prior to ore deposition (Gray and others, 1994). As a result, sulfide ore from these localities generates highly acidic drainage water with extreme concentrations of copper, intermediate concentrations of zinc (hundreds of ppm), and moderate concentrations of cobalt, nickel, arsenic, uranium, chromium, thorium, and rare earth elements (hundreds of ppb to tens of ppm). In contrast, carbonate-rich polymetallic ore, which replaces carbonate-rich sedimentary rock or is present in carbonate-rich wall rock, most commonly generates water with near neutral pH values; if the ore is pyrite-rich, associated drainage water can contain significant quantities of dissolved zinc (as high as 200 ppm) and lesser copper (as high as 1 ppm). As discussed above, for a given set of geologic characteristics, acidity and metal content progressively increase from water draining underground workings, to that draining mine waste dumps, to open-pit water; these progressive increases in acidity and metal content reflect increased accessibility of minerals to weathering, increased access to oxygenated water, and increased evaporative concentration.

Available data demonstrate the importance of metal sorption onto suspended particulates as a control on metal mobility into the environment from mine sites and weathering mineral deposits (Smith and others, 1994). The amounts of metals (such as lead, copper, and zinc) and other elements (such as arsenic) sorbed depend on (1) the amounts of suspended particulates present in the drainage water, (2) the pH of the water, and (3) the speciation and concentrations of the metals and arsenic in the drainage water. For example, zinc is an abundant metal in many mineral deposits, is relatively mobile during weathering, and is not as readily sorbed onto particulates as are lead or copper. Hence, zinc can remain largely dissolved throughout a range of pH values at which lead and copper are entirely or mostly sorbed. As a result, zinc is the dominant base metal in all of the mine-drainage water sampled in Colorado with pH values greater than 5.5 (fig. 1; Smith and others, 1994).

GEOENVIRONMENTAL MODELS OF MINERAL DEPOSITS

Our current working definition of a "geoenvironmental model" for a given mineral deposit type is: "A compilation of geologic, geochemical, geophysical, hydrologic, and engineering information pertaining to the environmental behavior of geologically similar mineral deposits (a) prior to mining, and (b) resulting from mining, mineral processing, and smelting." For each mineral deposit model, the associated geoenvironmental model summarizes environmentally pertinent geologic information such as ore, gangue, wall rock, and alteration mineralogy (acid-generating versus acid consuming, etc.); secondary oxidation mineralogy (soluble versus non-soluble); geologic



- ✕ Massive pyrite, sphalerite, galena, chalcopyrite lenses
- ★ Cobalt-rich massive sulfides
- Massive pyrite-sphalerite-galena in black shales
- Pyrite-enargite-chalcocite-covellite ores in acid-altered rocks
- ◆ Pyrite-native sulfur in acid-altered wallrocks
- ▼ Molybenite-quartz-fluorite veins and disseminations in U-rich igneous intrusions
- ▲ Pyrite-chalcopyrite disseminations in quartz-sericite-pyrite altered igneous rocks
- ◆ Pyrite-sphalerite-galena-chalcopyrite veins in rocks with low carbonate contents
- Pyrite veins and disseminations with low base metal contents in rocks with low carbonate contents
- ◀ Pyrite-sphalerite-galena-chalcopyrite veins, replacements in carbonate-rich sedimentary rocks
- Pyrite-sphalerite-galena-chalcopyrite veins with high carbonate contents or in rocks altered to contain carbonate minerals
- ⊙ Pyrite-poor gold-telluride veins and breccias with high carbonate contents
- ◻ Pyrite-poor sphalerite-galena veins and replacements in carbonate-bearing sedimentary rocks

Figure 1. Variations in aqueous base metal concentrations (given as the sum of base metals zinc, copper, cadmium, cobalt, nickel, and lead) as a function of pH for water draining various types of mineralized rock in diverse sites within Colorado.

controls on permeability, ground water flow, and oxidation; and other deposit types with similar environmental geology characteristics. Some of the environmental models presented in this compilation also provide available empirical data on environmental signatures that: (1) are present prior to mining in soil, stream sediment, and ground and surface water; (2) result from mining and mineral processing (mine drainage water, mine wastes, mill tailings and tailings water, and heap leach solutions), and (3) result from smelting (smelter slag and stack emissions). Environmental signatures include information concerning the elemental suites and their likely concentration in water, waste, and soil, etc., and the ease with which the elements can be liberated into the environment (their "geoavailability"). Empirical data from well characterized sites is lacking for some deposit types; potential environmental signatures for these deposit types can be extrapolated from similar deposits for which data are available. The models also include information, when available, on engineering and other types of processes that have been or likely can be used successfully to avoid, minimize, and remediate environmental signatures summarized in the models.

The geoenvironmental model for each deposit type is organized as follows:

I. SUMMARY OF RELEVANT GEOLOGIC, ENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

A summary of geoenvironmentally relevant information for each model includes:

- A. Deposit type geology
- B. Examples of deposits of this type
- C. Spatially or genetically related deposit types, listed by model name and number. In many mining districts, more than one deposit type may be present; each deposit type may have different associated geoenvironmental effects or concerns
- D. Potential environmental considerations: This section is designed to summarize environmental signatures that may be associated with each deposit type as well as some of the important geologic characteristics that affect these signatures
- E. Exploration geophysics

II. GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

This section discusses environmentally important geologic characteristics for each deposit type, including:

- A. Deposit size: The scale of associated environmental effects generally increases with increasing deposit size
- B. Host rocks: Host rock type influences factors such as mine-drainage compositions, trace element signatures, and ground-water hydrology
- C. Surrounding geologic terrane: The geologic characteristics of adjacent areas influence the environmental effects of deposits
- D. Wall-rock alteration: As with host rock type, wall-rock alteration can strongly affect environmental signatures, including mine-drainage compositions and local hydrology
- E. Nature of ore: Ore grain size, texture, and structural controls can strongly affect environmental signatures
- F. Deposit trace element geochemistry: Deposit trace element signatures are often inherited by various materials, including soil, stream sediment, and water, in the environment surrounding deposits
- G. Ore and gangue mineralogy and zonation: The minerals present in a deposit are the predominant control on environmental signatures. Spatial mineralogic variation can cause significant across-deposit variation of environmental signatures
- H. Mineral characteristics: Mineral textures and trace element contents influence the rate at which minerals weather and oxidize
- I. Secondary mineralogy: As deposits are exposed at the Earth's surface to processes such as weathering and erosion, new, more chemically stable, mineral suites develop. Minerals that form prior to mining as deposits weather are generally more stable than those that form as minerals exposed by mining weather
- J. Topography and physiography affect the position and shape of ground water tables, which in turn control the extent to which mines or mineral deposits are exposed to significant ground water flow
- K. Hydrology is strongly controlled by geologic characteristics of deposits, including whether ore is present as veins or lenses, both of which can focus ground water flow, or whether low-permeability barriers to ground water flow, such as clay-altered wallrock, are present
- L. Mining and milling methods employed are typically influenced strongly by the geologic characteristics of deposits. Both may change significantly over the life of a mine as technology evolves

III. ENVIRONMENTAL SIGNATURES

This section summarizes empirical data pertaining to environmental signatures; data have been gathered through field studies and (or) literature surveys

- A. Drainage signatures both natural and mining-related are summarized. Natural drainage data are required to define accurate pre-mining baseline conditions
- B. Metal mobility from solid mine wastes: Significant quantities of metal and acid can be stored as readily-dissolved, secondary mineral coatings on solid mine wastes
- C. Soil and sediment signatures prior to mining are also required to help establish pre-mining baseline conditions
- D. Potential environmental signatures associated with mineral processing
- E. Smelter signatures: Where possible, data concerning metal contents and mobility from slag and soils affected by smelter emissions are presented
- F. Climate effects on environmental signatures: This section discusses how environmental signatures vary as a function of climatic regime variation
- G. Guidelines for mitigation and remediation: This section, available for only a few models, is designed to provide insights into the types of engineering techniques that are commonly used to mitigate or remediate environmental effects likely to be associated with particular deposit types. In addition, deposit geologic features that might be used to develop more effective or less expensive remedial techniques are described
- H. Geoenvironmental geophysics: This section contains information on geophysical techniques that are of use to help identify, assess, or delineate environmental signatures

USES OF GEOENVIRONMENTAL MODELS

The main purpose of the geoenvironmental models described in this compilation is to provide impartial geoscience information that can be used to better understand, anticipate, minimize, and remediate the environmental effects of mineral deposits and mineral-resource development. Land managers can use the models to develop perspectives concerning historical and potential future environmental impacts related to mineral deposits. In addition, the models should be of some assistance in developing mitigation strategies and for ecosystem-based land management plans. Many of the models include data, such as natural pre-mining environmental baselines, which can be suitably applied during post-mining remediation endeavors. The models include objective information that is available to all concerned; they potentially benefit industry, regulators, land managers, and the general public. Some of the models present not only the potential environmental concerns likely to be associated with particular mineral deposit types, but also present information concerning how mineral-deposit-related environmental impact can be avoided, minimized, or remediated.

Establishment of pre-mining baseline conditions

It is more cost-effective, technologically feasible, and realistic to remediate mine sites to baseline (typically somewhat contaminated) conditions that existed in mineralized areas prior to mining, rather than to conditions that prevail in unmineralized areas. When possible, the models presented in this compilation include data on environmental signatures prior to mining or disturbance; such data are crucial to establish reasonable baseline conditions for diverse deposit types in various climates. These baseline models can then be used to establish analogues for pre-mining conditions in mining districts where historic mining activities have obscured pre-existing baseline conditions.

Exploration

Knowledge of likely environmental effects associated with development of particular deposit types can be integrated into grass-roots exploration efforts. For example, development of deposit types with typically high acid mine drainage generation potential, and extreme associated metal contents, will have lower environmental mitigation expenses in arid climates or in geologic terranes with abundant carbonate rocks than in other environments.

Mine planning and development

Improved predictive capabilities provided by environmental models will enable mine planners to better anticipate, plan for, and mitigate potential environmental problems, rather than to treat (with much greater technical difficulties and costs) environmental problems after they occur. Similarly, inherent geologic characteristics of a particular deposit can be exploited to help mitigate subsequent potential environmental problems. For example, carbonate-bearing wall-rock alteration commonly present on the fringes of deposits, or carbonate sedimentary rocks near some deposits, may be useful in acid drainage mitigation.

Remediation

The models presented in this compilation summarize crucial geologic, geochemical, and hydrologic information (such as geologic controls on ground water flow, ore mineralogy, and materials geology) needed by engineers to develop effective remediation plans at mine sites. Some remedial plans currently in implementation ignore or dangerously oversimplify important geologic information. For example, adit plugging has been used or is proposed to reduce acid drainage from a number of mine sites. The geoenvironmental models can be used to identify deposit types in which faults or other hydrologic conduits might be common, thereby reducing the effectiveness of adit plugging as a remedial solution. In addition, the models can be used to help identify likely types and orientations of faults and other hydrologic conduits present at remediation sites.

Abandoned mine lands issues

Although mineral resource extraction has been carried out for several millennia, minimizing associated environmental effects has received relatively little attention until the last several decades. As a result, a very large number of historic mining and mineral processing sites (those operated prior to the last several decades) that were abandoned once profitable ore was exhausted are now potential sources of environmental contamination. In the United States, land management agencies are currently faced with the daunting task of identifying and prioritizing for remediation all abandoned mine sites on public lands; although many sites do not require remediation, the total number of sites to be prioritized is likely in excess of several hundred thousand. The geoenvironmental models presented in this compilation provide land managers with a low-cost screening technique to help identify, prioritize for study, and develop remediation plans for hazardous mine sites on public lands.

REFERENCES CITED

- Alpers, C.N., and Blowes, D.W., eds., 1994, Environmental geochemistry of sulfide oxidation, ACS Symposium Series 550: Washington, D.C., American Chemical Society, 681 p.
- Anderson, J.A., 1982, Characteristics of leached capping and techniques of appraisal, *in* Titley, S.R., ed., *Advances in geology of the porphyry copper deposits*: Tucson, University of Arizona Press, 560 p.
- Bliss, J.D., 1992, Developments in mineral deposit modeling: U.S. Geological Survey Bulletin 2004, 168 p.
- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- FitzPatrick, E.A., 1980, *Soils--Their formation, classification, and distribution*: London, Longman, 353 p.
- Gray, J.E., Coolbaugh, M.F., Plumlee, G.S., and Atkinson, W.W., 1994, Environmental geology of the Summitville Mine, Colorado: *Economic Geology*, v. 89, p. 2006-2014.
- Guilbert, J. and Park, C., 1986, *The geology of ore deposits*: W.H. Freeman and Co., New York, 985 p.
- Jambor, J.L., and Blowes, D.W., eds., 1994, Short course on environmental geochemistry of sulfide-mine wastes: Mineralogical Association of Canada, Short Course Handbook, Volume 22, 438 p.
- Kwong, Y.T.J., 1993, Prediction and prevention of acid rock drainage from a geological and mineralogical perspective: MEND Project 1.32.1, 47 p.
- Plumlee, G.S., in press, The environmental geology of mineral deposits, *in* Plumlee, G.S., and Logsdon, M.J., eds., *The Environmental Geochemistry of Mineral Deposits-Part A; Processes, methods, and health issues*: Society of Economic Geologists Reviews in Economic Geology, Volume 6A.
- Plumlee, G.S., Smith, K.S., Ficklin, W.H., Briggs, P.H., and McHugh, J.B., 1993, Empirical studies of diverse mine drainages in Colorado--implications for the prediction of mine-drainage chemistry: *Proceedings, 1993 Mined Land Reclamation Symposium*, Billings, Montana, v. 1, p. 176-186.
- Rose, A.W., Hawkes, H.E., and Webb, J.S., 1979, *Geochemistry in mineral exploration (2nd Ed.)*: New York, Academic Press, 657 p.
- Ross, M., in press, The health effects of mineral dusts, *in* Plumlee, G.S., and Logsdon, M.J., eds., *The Environmental Geochemistry of Mineral Deposits-Part A; Processes, methods, and health issues*: Society of Economic Geologists Reviews in Economic Geology, Volume 6A.
- Smith, K.S., Plumlee, G.S., and Ficklin, W.H., 1994, Predicting water contamination from metal mines and mining waste: Notes, Workshop No. 2, International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage: U.S. Geological Survey Open-File Report 94-264, 112 p.

BIOAVAILABILITY OF METALS

by David A. John and Joel S. Leventhal

INTRODUCTION

The fate of various metals, including chromium, nickel, copper, manganese, mercury, cadmium, and lead, and metalloids, including arsenic, antimony, and selenium, in the natural environment is of great concern (Adriano, 1986; 1992), particularly near former mine sites, dumps, tailing piles, and impoundments, but also in urban areas and industrial centers. Soil, sediment, water, and organic materials in these areas may contain higher than average abundances of these elements, in some cases due to past mining and (or) industrial activity, which may cause the formation of the more bioavailable forms of these elements. In order to put elemental abundances in perspective, data from lands and watersheds adjacent to these sites must be obtained and background values, often controlled by the bedrock geology and (or) water-rock interaction, must be defined.

In order to estimate effects and potential risks associated with elevated elemental concentrations that result from natural weathering of mineral deposits or from mining activities, the fraction of total elemental abundances in water, sediment, and soil that are bioavailable must be identified. Bioavailability is the proportion of total metals that are available for incorporation into biota (bioaccumulation). Total metal concentrations do not necessarily correspond with metal bioavailability. For example, sulfide minerals may be encapsulated in quartz or other chemically inert minerals, and despite high total concentrations of metals in sediment and soil containing these minerals, metals are not readily available for incorporation in the biota; associated environmental effects may be low (Davis and others, 1994). Consequently, overall environmental impact caused by mining these rocks may be much less than mining another type of mineral deposit that contains more reactive minerals in lower abundance.

In aquatic environments where chemically reducing conditions may prevail, metals from mining activities may be associated with sulfide minerals. These sulfide minerals are present either in the ore deposit or formed by bacterial reduction of the sulfate in oxidized tailings. Most metal sulfide minerals are quite immobile, as long as they remain in a chemically reducing environment, and they may have little impact on biota despite anomalous metal concentrations.

BIOAVAILABILITY

Metals of major interest in bioavailability studies, as listed by the U.S. Environmental Protection Agency (EPA), are Al, As, Be, Cd, Cr, Cu, Hg, Ni, Pb, Se, and Sb (McKinney and Rogers, 1992). Other metals that are presently of lesser interest to the EPA are Ag, Ba, Co, Mn, Mo, Na, Tl, V, and Zn. These metals were selected because of their potential for human exposure and increased health risk. Some highlights concerning the bioavailability of As, Cd, Cu, Hg, Mo, Pb, Se, and Zn in water and (or) sediment are discussed in the section below entitled "Specific metals of interest."

Metals can be dispersed in soil, water, and air. Geoscientists are mainly concerned with metals dispersed in soil and sediment, dissolved in ground and surface water, suspended as particles in surface water, and in pore fluid in sediment (fig. 1). In addition, metals can be dispersed into the atmosphere, by natural geochemical cycling and by other anthropogenic processes (such as smelting and burning leaded gasoline and coal) and by microbial activities; these metal fluxes must be considered in overall metal bioavailability studies. Bioaccumulation of metals by biota in surface water and by plants and animals in terrestrial environments can adversely affect humans. In surface and ground water, sediment and air, bioavailability is a complex function of many factors including total concentration and speciation (physical-chemical forms) of metals, mineralogy, pH, redox potential, temperature, total organic content (both particulate and dissolved fractions), and suspended particulate content, as well as volume of water, water velocity, and duration of water availability, particularly in arid and semi-arid environments. In addition, wind transport and removal from the atmosphere by rainfall (frequency is more important than amount) must be considered. Many of these factors vary seasonally and temporally, and most factors are interrelated. Consequently, changing one factor may affect several others. In addition, generally poorly understood biological factors seem to strongly influence bioaccumulation of metals and severely inhibit prediction of metal bioavailability (Luoma, 1989). Some of the major controls on the bioavailability of metals in surface water and soil and data concerning potentially hazardous metals are described below.

In order to understand bioavailability, plant materials and selective chemical leaches of soil must be analyzed and the results compared. Elemental suites for which analyses are performed and the type of selective leaches utilized must be tailored to bedrock and soil types, and to suspected anthropogenic inputs. Soil pH, organic matter,

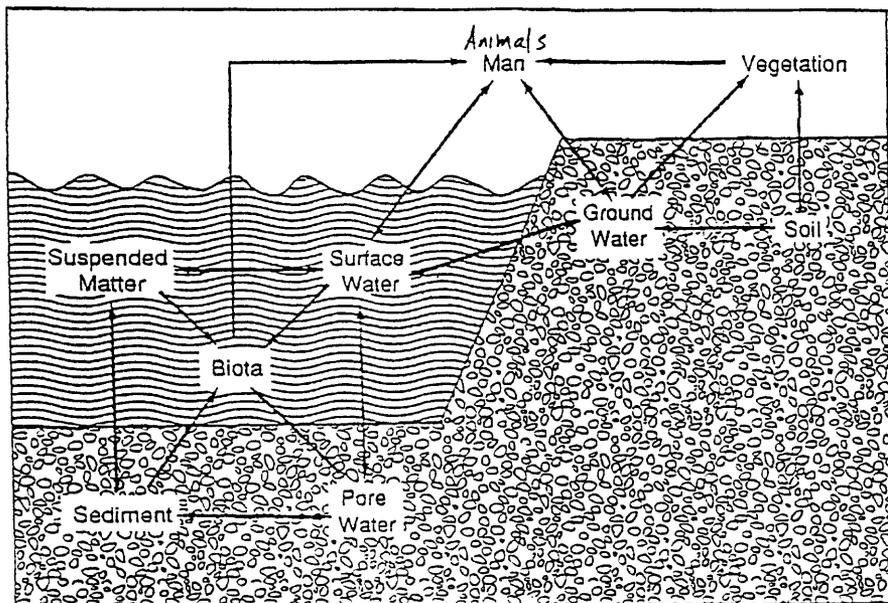


Figure 1. Interrelationships of man, metals, and the environment. Modified from Salomons and Förstner (1988).

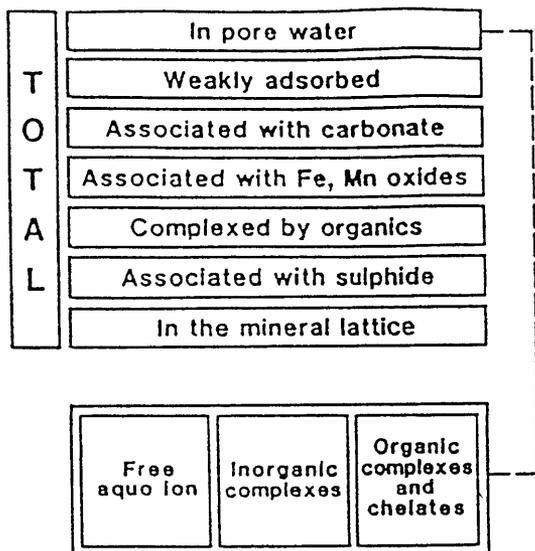


Figure 2. The chemical forms of metals in solid phases. Modified from Gunn and others (1988).

and sulfur and carbonate contents should be determined to enable accurate assessment of elemental reservoirs, mobility, and bioavailability. Additional work on mineralogical residences of metals is also important because metals can be associated with several sites (fig. 2).

Soil scientists involved in agriculture have been studying the chemistry of nutrient elements in soil for more than 100 years. Soil testing methods are used to determine sixteen essential elements for plant growth, but nitrogen, phosphorous, and potassium, along with pH and salinity are the most often measured properties (Peck and Soltanpour, 1990). Physical-chemical aspects of nutrient availability are discussed by Corey (1990) and soil testing correlations are reviewed by Dahnke and Olson (1990).

FACTORS THAT INFLUENCE BIOAVAILABILITY IN SOIL

Plant uptake of trace elements is generally the first step of their entry into the agricultural food chain. Plant uptake is dependent on (1) movement of elements from the soil to the plant root, (2) elements crossing the membrane of epidermal cells of the root, (3) transport of elements from the epidermal cells to the xylem, in which a solution of

Table 1. Relative mobility and availability of trace metals (modified from Salomons, 1995)

<u>Metal species and association</u>	<u>Mobility</u>
Exchangeable (dissolved) cations	High. Changes in major cationic composition (e.g. estuarine environment) may cause a release due to ion exchange
Metals associated with Fe-Mn oxides	Medium. Changes in redox conditions may cause a release but some metals precipitate if sulfide mineral present is insoluble
Metals associated with organic matter	Medium/High. With time, decomposition/oxidation of organic matter occurs
Metals associated with sulfide minerals	Strongly dependent on environmental conditions. Under oxygen-rich conditions, oxidation of sulfide minerals leads to release of metals
Metals fixed in crystalline phase	Low. Only available after weathering or decomposition

elements is transported from roots to shoots, and (4) possible mobilization, from leaves to storage tissues used as food (seeds, tubers, and fruit), in the phloem transport system. After plant uptake, metals are available to herbivores and humans both directly and through the food chain. The limiting step for elemental entry to the food chain is usually from the soil to the root (Chaney, 1988). This critical step usually depends on element concentrations in soil pore solutions, which are controlled by local soil physical and chemical conditions including water content, pH, Eh, and other factors.

Climate strongly influences soil types; these two factors largely control element (metals and metalloids) mobility and availability. Arid climates in the western United States often result in small soil organic matter abundances and large salt and carbonate abundances. These phases often contain the metals of interest. In the eastern United States, humid climates prevail and large amounts of organic matter require determination of organic matter-associated metals and their residence times or turn-over rates, because after some time, much of the organic matter is oxidized and associated metals may be released or available. In tropical climate conditions, accumulation of oxide minerals of iron, manganese, and aluminum in soil profiles may limit the mobility and bioavailability of both metals and metalloids.

Plant species and relative abundance and availability of necessary elements also control metal uptake rates. Abundant bioavailable amounts of essential nutrients, including phosphorous and calcium, can decrease plant uptake of non-essential but chemically similar elements, including arsenic and cadmium, respectively. More complex interactions are also observed: bioavailability may be related to multi-element amounts or ratios. For example, copper toxicity is related to low abundances of zinc, iron, molybdenum and (or) sulfate (Chaney, 1988). Many agricultural studies have been completed on this subject (see Adriano, 1986; 1992).

In the scientific literature, many studies describe anthropogenic (industrial or mining) contributions to elemental abundances, and their bioavailability controls, in the environment. Examples include: occurrence of heavy metals in soil near and far from urban pollution (Pouyat and McDonnell, 1991); formation of acid mine drainage (Filipek and others, 1987); uptake of heavy metals by plants in lab experiments (Brown and others, 1995); and uptake of metals by vertebrates in the vicinity of zinc smelters (Storm and others, 1994).

FACTORS THAT INFLUENCE PARTITIONING OF METALS IN SURFACE WATER AND SEDIMENT

After discharge to an aquatic environment but before uptake by organisms, metals are partitioned between solid and liquid phases. Within each phase, further partitioning occurs among ligands as determined by ligand concentrations and metal-ligand bond strengths. In solid phases, soil, sediment, and surface water particulates, metals may be partitioned into six fractions: (a) dissolved, (b) exchangeable, (c) carbonate, (d) iron-manganese oxide, (e) organic, and (f) crystalline (Elder, 1989; Salomons, 1995). Various metals partition differently among these fractions as shown by sequential partial extraction procedures. Partitioning is affected strongly by variations in pH, redox state, organic content, and other environmental factors (Elder, 1989; Salomons, 1995). The relative mobility and bioavailability of trace metals associated with different fractions are shown in Table 1. The dissolved fraction consists of carbonate complexes, whose abundance increases with pH, and metals in solution, including metal cation and anion complexes and hydrated ions whose solubilities are affected strongly by pH and tend to increase with decreasing pH (Elder, 1989). Exchangeable fractions consist of metals bound to colloidal or particulate material.

Metals associated with carbonate minerals in sedimentary rocks and soil constitute the carbonate fraction, which can be newly precipitated in soil. The iron-manganese oxide fraction consists of metals adsorbed to iron-manganese oxide particles or coatings. The organic fraction consists of metals bound to various forms of organic matter. The crystalline fraction consists of metals contained within the crystal structure of minerals and normally not available to biota.

Hydrogen ion activity (pH) is probably the most important factor governing metal speciation, solubility from mineral surfaces, transport, and eventual bioavailability of metals in aqueous solutions. pH affects both solubility of metal hydroxide minerals and adsorption-desorption processes. Most metal hydroxide minerals have very low solubilities under pH conditions in natural water. Because hydroxide ion activity is directly related to pH, the solubility of metal hydroxide minerals increases with decreasing pH, and more dissolved metals become potentially available for incorporation in biological processes as pH decreases. Ionic metal species also are commonly the most toxic form to aquatic organisms (Salomons, 1995).

Adsorption, which occurs when dissolved metals are attached to surfaces of particulate matter (notably iron, manganese, and aluminum oxide minerals, clay, and organic matter), is also strongly dependent on pH and, of course, the availability of particulate surfaces and total dissolved metal content (Bourg, 1988; Elder, 1989). Metals tend to be adsorbed at different pH values, and sorption capacity of oxide surfaces generally varies from near 0 percent to near 100 percent over a range of about 2 pH units.

The adsorption edge, the pH range over which the rapid change in sorption capacity occurs, varies among metals, which results in precipitation of different metals over a large range of pH units. Consequently, mixing metal-rich, acidic water with higher pH, metal-poor water may result in dispersion and separation of metals as different metals are adsorbed onto various media over a range of pH values. Cadmium and zinc tend to have adsorption edges at higher pH than iron and copper, and consequently they are likely to be more mobile and more widely dispersed. Adsorption edges also vary with concentration of the complexing agent; thus, increasing concentrations of complexing agent increases pH of the adsorption edge (Bourg, 1988). Major cations such as Mg^{+2} and Ca^{+2} also compete for adsorption sites with metals and can reduce the amount of metal adsorption (Salomons, 1995).

Particulate size and resulting total surface area available for adsorption are both important factors in adsorption processes and can affect metal bioavailability (Luoma, 1989). Small particles with large surface-area-to-mass ratios allow more adsorption than an equivalent mass of large particles with small surface-area-to-mass ratios. Reduced adsorption can increase metal bioavailability by increasing concentrations of dissolved metals in associated water. The size of particles released during mining depends on mining and beneficiation methods. Finely milled ore may release much smaller particles that can both be more widely dispersed by water and wind, and which can also serve as sites of enhanced adsorption. Consequently, mine tailings released into fine-grained sediment such as silty clays found in many playas can have much lower environmental impact than those released into sand or coarse-grained sediment with lower surface area and adsorption.

Temperature exerts an important effect on metal speciation, because most chemical reaction rates are highly sensitive to temperature changes (Elder, 1989). An increase of 10°C can double biochemical reaction rates, which are often the driving force in earth surface conditions for reactions that are kinetically slow, and enhance the tendency of a system to reach equilibrium. Temperature may also affect quantities of metal uptake by an organism, because biological process rates (as noted above) typically double with every 10°C temperature increment (Luoma, 1983; Prosi, 1989). Because increased temperature may affect both influx and efflux rates of metals, net bioaccumulation may or may not increase (Luoma, 1983).

In recent organic carbon-rich sediments, trapped interstitial fluids can commonly form a strongly reducing (anoxic) environment. Low redox potential in this environment can promote sulfate reduction and sulfide mineral deposition. During diagenesis, much of the non-silicate-bound fraction of potentially toxic metals such as arsenic, cadmium, copper, mercury, lead, and zinc, can be co-precipitated with pyrite, form insoluble sulfides, and become unavailable to biota (Morse, 1994). Seasonal variation in flow rates or storms that induce an influx of oxygenated (sea)water can result in rapid reaction of this anoxic sediment and thereby release significant proportions of these metals. Pyritization and (or) de-pyritization of trace metals probably can be an important process in controlling bioavailability of many trace metals, especially in the marine environment (Morse, 1994).

METAL UPTAKE PATHS INTO AQUATIC ORGANISMS

Metal uptake by plants (discussed above) and partitioning in the soil (above) are combined in the aquatic environment. Two major pathways or uptake vectors are available for metal incorporation in deposit- and (or)

detritus-feeding aquatic species: (1) ingestion of metal-enriched sediment and suspended particles during feeding, and (2) uptake from solution (Luoma, 1989). Consequently, knowledge of geochemical reactions of metals in both water and sediment is necessary to understand controls on metal bioavailability in natural water. Unfortunately, many biological factors controlling metal bioaccumulation in aquatic organisms are not understood; this fact severely limits our understanding of metal bioavailability (Luoma, 1989).

Bioavailability studies indicate that aquatic organisms uptake free metal ions (metal hydroxides) from solution quite efficiently; similarly, terrestrial animals uptake metal from solutions more efficiently than via direct particulate matter ingestion (Luoma, 1983). Consequently, geologic and (or) environmental conditions that enhance dissolved metal abundances (for example, lower pH) result in greater metal bioavailability. Indirect controls, such as larger particle or sediment size, also can result in greater bioavailability of metals by reducing adsorption and increasing dissolved metal contents. Metal assimilation from ingested particulate matter is also important, however, because metals are highly concentrated in this form (Luoma, 1989).

The efficiency of bioaccumulation via sediment ingestion is dependent on geochemical characteristics of the sediment. Luoma (1989) describes variation of cadmium uptake from sediment by clams as a function of sediment iron content; cadmium uptake from iron oxide-rich sediment was not detected, but a significant proportion of total cadmium uptake was a consequence of iron-poor sediment ingestion by clams.

GEOCHEMICAL AND ENVIRONMENTAL PROCESSES THAT AFFECT BIOAVAILABILITY

Numerous geochemical environmental factors may affect metal availability to aquatic organisms and plants (discussed in previous sections). The most important factors appear to be: (1) metal concentrations of solutions, (2) solute metal speciation, (3) metal concentration in food, (4) metal partitioning among ligands within food, (5) influence of other cations, (6) temperature, (7) pH, and (8) redox potential (Luoma, 1983). Several of these factors are described above and others are discussed in the following paragraphs.

Interaction among metals can result both in stimulation and antagonism, as described by Luoma (1989). Stimulation occurs when uptake of one metal induces synthesis of binding sites that affect accumulation of both metals. Stimulation of cadmium uptake by lead exposure and of zinc by cadmium exposure have been observed in rats. Antagonism is commonly observed in simultaneous exposure to several metals. Antagonism to zinc uptake occurs during exposure to cobalt in clams and to copper in phytoplankton and microalgae. Antagonism between zinc and cadmium occurs in phytoplankton and macroalgae. Antagonism between copper and lead and between cadmium and mercury has also been reported in some types of organisms. In addition, more widespread elements, such as calcium and magnesium, can inhibit some types of metal-organic interactions. Zinc uptake by fish is influenced by this phenomenon but uptake of copper and cadmium are not affected.

Empirical studies suggest that bioavailability of several potentially toxic cationic metals (cadmium, cobalt, copper, nickel, and zinc) in anaerobic sediment is dependent on the total concentration of these elements in pore fluids (Ankley and others, 1994). They suggest that bioavailability of these metals can be predicted by measuring the acid volatile sulfide (AVS) and the simultaneously extracted metal (SEM) contents of sediment. AVS is the fraction of sulfide extracted by cold HCl and consists primarily of iron-sulfide complexes, whereas SEM is a sum of the concentrations of metals simultaneously extracted with AVS. High toxicity levels in benthic invertebrates and presumably high bioavailability of these metals are present when the SEM-AVS ratio exceeds one.

As noted above, temperature can strongly influence the rate of biological processes; rates double for every 10°C-temperature increment. The increase in biological process rates does not necessarily result in increased bioaccumulation of metals, because both influx and efflux rates of metals may increase.

Transport of metals may vary between relatively unpolluted systems and disturbed or polluted systems. Particulate transport is dominant in unpolluted systems where metal inputs are principally from erosion of watershed substrates (Elder, 1989). In disturbed or polluted systems, for example, those affected by acid-mine drainage, point sources commonly deliver metals in a soluble phase, or associated with organic matter, and the proportion of dissolved metals and their bioavailability tends to be higher (Salomons and Forstner, 1984).

DETERMINATION OF BIOAVAILABILITY BY SELECTIVE CHEMICAL EXTRACTION

The extent of bioavailability is largely controlled by elemental speciation or chemical siting in soil, which determine solubility. A number of soil testing methods and partial or sequential chemical extraction techniques and methods are used to determine element behavior (Chao, 1984; Gunn and others, 1988). Some of the chemical extractions are: (1) water or MgCl₂ at neutral or ambient soil pH for easily soluble metals, (2) solubility in weak base (pH 9) for humic materials, (3) weak acid or dilute acid in buffer solution (pH 2 to 5) to release metals associated with

carbonate phases, and (4) a chelating (or complexing) agent such as EDTA (ethylenediaminetetraacetic acid) (Borggaard, 1976) or DPTA (diethylenetriaminepentaacetic acid) buffered to a pH of 7 (Crock and Severson, 1980). Other possible extractants include (5) hydroxylamine hydrochloride for the "reducible" fraction associated with iron and manganese oxides/hydroxides, (6) strong acid (HCl, pH 1) to identify maximum mobility of most metals (Leventhal and Taylor, 1990), (7) oxidation by hydrogen peroxide to release metals associated with organic matter and (or) sulfide minerals, (8) a strong oxidizing acid (HNO_3) to execute steps (6) and (7) simultaneously, and (9) a mixture of strong acid and HF to dissolve residual silicate minerals. The choice of extractants and the order in which they are used depends on the sediment/soil type, environmental conditions, and metals of interest.

However, these sequential/partial extractions are all "operational", that is they are not completely specific to metals or chemical phases. Therefore any determination of bioavailability should be carefully calibrated, by direct measurement, with the actual behavior of metals in soil and plants. For example, O'Connor (1988) cautions about the use of the DPTA method and shows that it sometimes gives results comparable to plant uptake and sometimes it does not. As a consequence, he advises direct analysis of the total plant and (or) its component parts in addition to chemical leaches in order to determine bioavailability.

SPECIFIC METALS OF INTEREST

Brief summaries of some factors controlling bioavailability of several metals and two metalloids are given below. Additional data are available in the references listed for each metal.

Arsenic: Arsenic mobility, bioavailability, and toxicity are dependent on speciation: arsenite (AsO_3^{-3}) forms are much more toxic to biological species and are more mobile than arsenate (AsO_4^{-3}) forms (Kersten, 1988). Arsenic is chemically similar to phosphorous. Arsenate interferes with phosphate metabolism that is widespread in the biosphere. Metallo-organic forms of arsenic also may be much more bioavailable than inorganic forms; however, organic-bound arsenic is excreted by most species and does not appear to be highly toxic (Luoma, 1983). Adsorption-desorption on iron and aluminum oxide minerals is the main factor controlling arsenic behavior in soil and sediment. Maximal adsorption occurs at different pH for As{III} (pH 9.2) and As{V} (pH 5.5) as a function of the adsorbing mineral; As^{+3} mobility is enhanced under oxic conditions. Arsenic is apparently highly mobile in anoxic sediment-water systems. Development of acidic and oxidizing conditions tends to release large amounts of arsenic into solution due to decreased sorption capacity of both forms of arsenic (see Léonard, 1991).

Cadmium: The redox potential of sediment-water systems exerts controlling regulation on the chemical association of particulate cadmium, whereas pH and salinity affect the stability of its various forms (Kersten, 1988). In anoxic environments, nearly all particulate cadmium is complexed by insoluble organic matter or bound to sulfide minerals. Greenockite (CdS) has extremely low solubility under reducing conditions thereby decreasing cadmium bioavailability. Oxidation of reduced sediment or exposure to an acidic environment results in transformation of insoluble sulfide-bound cadmium into more mobile and potentially bioavailable hydroxide, carbonate, and exchangeable forms (Kersten, 1988). Studies of lake and fluvial sediment indicate that most cadmium is bound to exchangeable site, carbonate fraction, and iron-manganese oxide minerals, which can be exposed to chemical changes at the sediment-water interface, and are susceptible to remobilization in water (Schintu and others, 1991). In oxidized, near neutral water, CdCO_3 limits the solubility of Cd^{2+} (Kersten, 1988). In a river polluted by base-metal mining, cadmium was the most mobile and potentially bioavailable metal and was primarily scavenged by non-detrital carbonate minerals, organic matter, and iron-manganese oxide minerals (Prusty and others, 1994). Elevated chloride contents tend to enhance chloride complex formation, which decreases the adsorption of cadmium on sediment, thereby increasing cadmium mobility (Bourg, 1988) and decreasing the concentration of dissolved Cd^{+2} and bioavailability (Luoma, 1983). Also see, Stoeppler (1991) for additional data.

Copper: In a river polluted by base-metal mining, copper is most efficiently scavenged by carbonate minerals and iron-manganese oxide minerals and coatings and is less mobile than cadmium, lead, and zinc (Prusty and others, 1994); in most other situations lead is less mobile than copper. Elevated chloride contents decrease adsorption of copper on sediment, due to chloride complexation, which results in greater solubility and mobility (Bourg, 1988; Gambrell and others, 1991). In systems with high total copper contents, precipitation of malachite controls dissolved copper contents at low pH (Bourg, 1988; Salomons, 1995). Sometimes, elemental substitution is more complex; for example, copper toxicity is related to low abundances of zinc, iron, molybdenum, and (or) sulfate (Chaney, 1988).

Lead: The main sources of lead in the aquatic environment are leaded gasoline and mining (Prosi, 1989). Leaded gasoline results in introduction of organometallic lead compounds, which eventually reach surface water, into the atmosphere. Mining releases inorganic lead compounds. Both organic and inorganic forms of lead pose serious health risks to all forms of life (Ewers and Schlipkötter, 1990). Inorganic lead compounds (sulfide, carbonate, and sulfate minerals) are commonly abundant in sediment but have low solubilities in natural water. Naturally-occurring lead in mineral deposits is not very mobile under normal environmental conditions, but becomes slightly more soluble under moderately acidic conditions. Soluble lead is little affected by redox potential (Gambrell and others, 1991). Lead is tightly bound under strongly reducing conditions by sulfide mineral precipitation and complexation with insoluble organic matter, and is very effectively immobilized by precipitated iron oxide minerals under well-oxidized conditions (Gambrell and others, 1991). In the aquatic environment, total dissolved lead abundances in water and pore water control primary uptake by organisms. Lead bioaccumulation is primarily dependent on the amount of active lead compounds (predominantly aqueous species) in the environment and the capacity of animal species to store lead (Prosi, 1989). Particulate lead may contribute to bioaccumulation in organisms. For humans, particles that are inhaled but not exhaled are especially important. Variations in physiological and ecological characteristics of individual species lead to different enrichment factors and tolerances for each organism. Studies of bottom dwelling organisms suggests that iron-rich sediment inhibits lead bioavailability (Luoma, 1989). In a study of lake and fluvial sediment, most lead was bound to a carbonate fraction or to iron-manganese oxide minerals, both of which respond to chemical changes at the sediment-water interface, and are susceptible to remobilization in water (Schintu and others, 1991). In a polluted river environment, lead is most efficiently scavenged by non-detrital carbonate and iron-manganese oxide minerals and is less mobile than cadmium (Prusty and others, 1994).

Mercury: Mercury has three valence states in natural sediment-water systems: elemental mercury (Hg^0), Hg^{+1} , and Hg^{+2} (Kersten, 1988). Hg^0 is considerably more bioavailable for certain organisms than Hg^{+2} because of the solubility of Hg^0 in lipid-rich tissue (Luoma, 1983). However, Hg^{+2} is readily available to plants, but under reducing conditions and in presence of free sulfide ligands, mercury is stabilized in the Hg^{+2} state as extremely insoluble sulfide mineral precipitates or is bound as surface complexes with organic matter containing sulfur. Methylation of Hg^{+2} in natural environments leads to formation of volatile organic complexes that are several times more bioavailable than inorganic forms of mercury. Methylated mercury species are also one of the most toxic pollutants in the biosphere. Natural production of methyl mercury occurs under anoxic conditions and is probably mediated by microbes, but methylation of Hg^{+2} is inhibited by elevated sulfide contents (Kersten, 1988). Increased pH appears to increase availability of mercury to marsh plants possibly by causing conversion of Hg^{+2} to Hg^0 . Sediment can serve as a sink for mercury discharged to the environment; partition coefficients, between suspended matter and water, are usually in the range of 10^5 (Kersten, 1988). Sorption is the main process for enrichment of mercury in sediment. Sorption can be influenced by chloride ligand concentration due to formation of chloro-mercurial complexes; in seawater, only organic matter retains its sorption capacity for mercury. Most particulate mercury in natural aquatic environments is associated with humic and other organic materials as well as oxide and sulfide minerals. Several studies have shown that mercury is less bioavailable in sediment that is rich in organic matter (Luoma, 1989). Most mercury released from point sources during mining is bound to sulfide compounds and is relatively non-bioavailable. However, a large percentage of mercury becomes associated with organic complexes downstream from point sources, possibly due to mobilization of mercury from pore fluids by humic acids. In natural water, suspended matter is the main transporting medium for mercury. In oxic sediment, most mercury is bound in unknown (complexed?) chemical forms that are readily susceptible to transformation, thereby affecting its mobilization and bioavailability.

Molybdenum: Molybdenum is an essential element for many animals and plants as it is required in their enzyme system. Molybdenum can be present in molybdate anions, MoO_4^{2-} , in soil where it can be mobile and bioavailable, because it is geochemically similar to sulfate. Molybdate ion is often associated with iron oxyhydroxide minerals, where it competes with phosphate and organic matter. Molybdenosis in animals is associated with soil that contains large amounts of available molybdenum, especially in forage plants with low sulfur and copper contents (Neuman and others, 1987).

Selenium: In the arid western United States, a number of environmental problems are related to high selenium abundances. These problems are mainly due to irrigation practices that allow selenium to accumulate in drains, reservoirs, and wetlands. Under these conditions, selenium can be bioavailable to plants and birds and accumulate to toxic levels (Severson and Gough, 1992). Extensive work has been done by the U.S. Geological Survey to

determine the geochemistry of selenium, most of which is associated with (adsorbed on) oxide minerals, such as goethite (Balistrieri and Chao, 1987), amorphous iron oxyhydroxide and manganese oxide minerals (Balistrieri and Chao, 1990), and is relatively immobile. A chemical leach using 0.1 M KH_2PO_4 can be used to determine the soluble-available selenium (mainly as SeO_4^{2-}) content of soil with low oxide mineral contents and high pH (Chao and Sanzolone, 1989).

Zinc: In slightly basic, anoxic marsh sediment environments, zinc is effectively immobilized and not bioavailable (Gambrell and others, 1991). Substantial amounts of zinc are released to solution if this sediment is oxidized or exposed to an acidic environment. Very high abundances of soluble zinc are present under well oxidized conditions and at pH 5 to 6.5, whereas low abundances of soluble zinc are present at pH 8 under all redox conditions and at pH 5 to 6.5 under moderately and strongly reducing conditions (Gambrell and others, 1991). In polluted river environments, most zinc is scavenged by non-detrital carbonate minerals, organic matter, and oxide minerals and is less mobile than cadmium (and perhaps less mobile than lead) (Prusty and others, 1994). Elevated chloride contents decrease adsorption of zinc on sediment (Bourg, 1988).

SUMMARY

Bioavailability of metals released from mineral deposits is very complex and dependent on many interrelated chemical, biological, and environmental processes. These processes may vary over time and among micro-organisms, plants, and animals. In soil and surface water, the mining method, presence or absence of sulfide minerals, quantity of water, acid-buffering capacity, presence of organic matter and iron and manganese oxide minerals, element speciation, and concentrations of other constituents in water may impact dissolved and bioavailable metal and metalloid contents. Field and laboratory studies of particular sites using soil, plants, and selective chemical extraction methods may enhance understanding this environmental concern.

REFERENCES CITED

- Adriano, D.C., 1986, Trace elements in the terrestrial environment, Springer-Verlag, N.Y., 533 p.
- Adriano, D.C., (editor), 1992, Biogeochemistry of trace metals, Lewis Publications, Boca Raton, Fla., 514 p.
- Ankley, G.T., Thomas, N.A., DiToro, D.M., Hansen, D.J., Mahony, J.D., Berry, W.J., and Swartz, R.C., 1994, Assessing potential bioavailability of metals in sediments: A proposed approach: Environmental Management, v. 18, no. 3, p. 331-337.
- Balistrieri, L.S., and Chao, T.T., 1987, Selenium adsorption by goethite: Soil Science Society of America Journal, v. 51, p. 1145-1151.
- Balistrieri, L.S., and Chao, T.T., 1990, Adsorption of selenium by amorphous iron oxyhydroxide and manganese dioxide: Geochimica et Cosmochimica Acta, v. 54, p. 739-51.
- Borggaard, O.K., 1976, The use of EDTA in soil analysis: Acta Agriculturae Scandinavica, v. 26, p. 144-150.
- Bourg, A.C.M., 1988, Metals in aquatic and terrestrial systems: Sorption, speciation, and mobilization, in Salomons, W., and Forstner, U., eds., Chemistry and biology of solid waste: Berlin, Springer-Verlag, p. 3-32.
- Brown, S.L., Chaney, R.L., Angle, J.S., and Baker, A.J.M., 1995, Zinc and cadmium uptake by hyperaccumulator *Thlaspi caerulescens* grown in nutrient solution: Soil Science Society of America Journal, v. 59, p.125-33.
- Chaney, R.L., 1988, Metal speciation and interaction among elements affect trace element transfer in agricultural and environmental food-chains, in Kramer, J.R., and Allen, H.E., eds., Metal Speciation: Theory, Analysis and Application, Lewis Publications, Boca Raton, Fla., p. 219-259.
- Chao, T.T., 1984, Use of partial dissolution techniques in exploration geochemistry: Journal of Geochemical Exploration, v. 20, p. 101-135.
- Chao, T.T. and Sanzolone, R.F., 1989, Fractionation of soil selenium by sequential partial dissolution: Soil Science Society of America Journal, v. 53, p. 385-392.
- Corey, R.B., 1990, Physical-chemical aspects of nutrient availability, in Westerman, R.L., ed., Soil Testing and Plant Analysis, third edition, Soil Science Society of America, Madison, Wis., p. 11-24.
- Crock, J.G., and Severson, R.C., 1980, Four reference soil and rock samples for measuring element availability in the western energy regions: U.S. Geological Survey Circular 841, 16 p.
- Dahnke, W.C. and Olson, R.A., 1990, Soil test correlation, calibration, and recommendation, in Westerman, R.L., ed., Soil Testing and Plant Analysis, third edition, Soil Science Society of America, Madison, Wis., p. 45-71.

- Davis, Andy, Ruby, M.V., and Bergstrom, P.D., 1994, Factors controlling lead bioavailability in the Butte mining district, Montana, USA: *Environmental Geochemistry and Health*, v. 3/4, p. 147-157.
- Elder, J.F., 1989, Metal biogeochemistry in surface-water systems—A review of principles and concepts: U.S. Geological Survey Circular 1013, 43 p.
- Ewers, Ulrich, and Schlipkötter, Hans-Werner, 1990, Lead, *in* Merian, Ernest, ed., *Metals and Their Compounds in the Environment*: Weinheim, Germany, VCH, p. 971-1014.
- Filipek, L.H., Nordstrom, D.K., and Ficklin, W.H., 1987, Interaction of acid mine drainage with waters and sediments of West Squaw Creek in the West Shasta Mining District, California: *Environmental Science Technology*, v. 21 p. 388-96.
- Gambrell, R.P., Wiesepape, J.B., Patrick, W.H., Jr., and Duff, M.C., 1991, The effects of pH, redox, and salinity on metal release from a contaminated sediment: *Water, Air, and Soil Pollution*, v. 57-58, p. 359-367.
- Gunn, A.M., Winnard, D.A., and Hunt, D.T.E., 1988, Trace metal speciation in sediments and soils, *in* Kramer, J.R., and Allen, H.E., eds., *Metal Speciation: Theory, Analysis and Application*, Lewis Publications, Boca Raton, Fla., p. 261-294.
- Kersten, M., 1988, Geochemistry of priority pollutants in anoxic sludges: Cadmium, arsenic, methyl mercury, and chlorinated organics, *in* Salomons, W., and Forstner, U., eds., *Chemistry and biology of solid waste*: Berlin, Springer-Verlag, p. 170-213.
- Léonard, Alain, 1991, Arsenic, *in* Merian, Ernest, ed., *Metals and Their Compounds in the Environment*: Weinheim, Germany, VCH, p. 751-774.
- Leventhal, J. and Taylor, C., 1990, Comparison of methods to determine degree of pyritization: *Geochimica et Cosmochimica Acta*, v. 54, p. 2621-2625.
- Luoma, S.N., 1983, Bioavailability of trace metals to aquatic organisms—A review: *The Science of the Total Environment*, v. 28, p. 1-22.
- _____ 1989, Can we determine the biological availability of sediment-bound trace elements?: *Hydrobiologia*, v. 176/177, p. 379-396.
- McKinney, James, and Rogers, Ron, 1992, Metal bioavailability: *Environmental Science and Technology*, v. 26, p. 1298-1299.
- Morse, J.W., 1994, Interactions of trace metals with authigenic sulfide minerals: Implications for their bioavailability: *Marine Chemistry*, v. 46, p. 1-6.
- Neuman, D.R., Shrack, J.L., and Gough, L.P., 1987, Copper and molybdenum, *in* Williams, R.D., and Shuman, G.E., eds., *Reclaiming mine soils and overburden in western U.S.*: Soil Conservation Society of America, Ankeny, Iowa, p. 215-232.
- O'Connor, G.A., 1988, Use and misuse of the DPTA soil test: *Journal of Environmental Quality*, v. 17, p. 715-718.
- Peck, T.R. and Soltanpour, P.N., 1990, The principles of soil testing, *in* Westerman, R.L., ed., *Soil Testing and Plant Analysis*, third edition, Soil Science Society of America, Madison, Wis., p. 1-9.
- Pouyat, R.V., and McDonnell, M.J., 1991, Heavy metal accumulation in forest soils along an urban-rural gradient in southeastern New York: *Water, Soil, and Air Pollution*, v. 57-58, p. 797-807.
- Prosi, Fritz, 1989, Factors controlling biological availability and toxic effects of lead in aquatic organisms: *The Science of the Total Environment*, v. 79, p. 157-169.
- Prusty, B.G., Sahu, K.C., and Godgul, G., 1994, Metal contamination due to mining and milling activities at the Zawar zinc mine, Rajasthan, India. 1. Contamination of stream sediments: *Chemical Geology*, v. 112, p. 275-292.
- Salomons, W., 1995, Environmental impact of metals derived from mining activities: Processes, predictions, prevention: *Journal of Geochemical Exploration*, v. 52, p. 5-23.
- Salomons, W., and Förstner, U., 1984, *Metals in the Hydrocycle*: Berlin, Springer, 349 p.
- _____ eds., 1988, *Chemistry and biology of solid waste*: Berlin, Springer-Verlag, 305 p.
- Schintu, M., Kudo, A., Sarritzu, G., and Contu, A., 1991, Heavy metal distribution and mobilization in sediments from a drinking water reservoir near a mining area: *Water, Air, and Soil Pollution*, v. 57-58, p. 329-338.
- Severson, R.C. and Gough, L.P., 1992, Selenium and sulfur relationships in alfalfa and soil under field conditions, San Joaquin Valley, California: *Journal of Environmental Quality*, v. 21, p. 353-58.
- Stoeppler, Markus, 1991, Cadmium, *in* Merian, Ernest, ed., *Metals and Their Compounds in the Environment*: Weinheim, Germany, VCH, p. 803-851.
- Storm, G.L., Fosmire, G.J., and Bellis, E.D., 1994, Persistence of metals in soil and selected vertebrates in the vicinity of the Palmerton zinc smelters: *Journal of Environmental Quality*, v. 23, p. 508-514.

GEOPHYSICAL METHODS IN EXPLORATION AND MINERAL ENVIRONMENTAL INVESTIGATIONS

by Donald B. Hoover, Douglas P. Klein, and David C. Campbell

INTRODUCTION

In the following discussion, the applicability of geophysical methods to geoenvironmental studies of ore deposits is reviewed. Details of geophysical techniques are not emphasized; these are covered in standard texts (Society of Exploration Geophysicists, 1966; 1990) and have been summarized in Hoover and others (1992).

Various geophysical methods are identified in table 1 (adapted from a chart compiled by Compañie General de Geophysique, Massy, France and published with modification by Van Blaricom, 1980). The table identifies the utility of each method in airborne, ground, or borehole applications. Borehole methods are a specialized branch of geophysics that are not emphasized here. However, where ground disturbance is not prohibited, or where drillholes exist, there are a variety of useful borehole, crosshole, and borehole-surface techniques that may aid geoenvironmental studies (Mwenifumbo, 1993).

Table 1 also outlines physical parameters and properties, anomaly sources, and depth of investigation for each method. If a feature of geoenvironmental concern does not have an associated, measurable, physical property then geophysical investigations are not applicable. Depth of burial (of contaminant plumes, for instance) is extremely important in assessing the potential applicability of geophysics in geoenvironmental hazards identification. Geophysical responses for more deeply buried sources decrease in amplitude and increase in spatial wavelength until they disappear into geologic noise. Physical properties of cover, host rock, and mineral waste strongly influence responses of potentially hazardous material and are also important for evaluating the utility of a method in geoenvironmental investigations.

Some geophysical methods, such as gamma-ray spectrometry and remote sensing, measure surface attributes; others, such as thermal and some electrical methods are limited to detecting relatively shallow features but may help identify features at greater depth. Secondary effects of deeper features, such as geochemical haloes, can often be identified by these methods.

Geophysical modeling provides generalized and non-unique solutions to questions concerning the geometry of subsurface geologic relations. The non-uniqueness of these solutions is both a mathematical problem and one related to the multiplicity of sources that can cause geophysical anomalies. This feature is an implicit uncertainty in the discussion that follows. Environmental geophysics, like exploration geophysics, requires complimentary geophysical surveys integrated with geochemical and geologic insight.

This presentation first summarizes geophysical methods. Following the methods summary, geophysical strategies (that usually employ multi-technique approaches) for specific geoenvironmental investigations are discussed.

GRAVITY METHOD

Gravity measurements define anomalous density within the Earth; in most cases, ground-based gravimeters are used to precisely measure variations in the gravity field at different points. Gravity anomalies are computed by subtracting a regional field from the measured field, which result in gravitational anomalies that correlate with source body density variations. Positive gravity anomalies are associated with shallow high density bodies, whereas gravity lows are associated with shallow low density bodies. Thus, deposits of high-density chromite, hematite, and barite yield gravity highs, whereas deposits of low-density halite, weathered kimberlite, and diatomaceous earth yield gravity lows. The gravity method also enables a prediction of the total anomalous mass (ore tonnage) responsible for an anomaly. Gravity and magnetic (discussed below) methods detect only lateral contrasts in density or magnetization, respectively. In contrast, electrical and seismic methods can detect vertical, as well as lateral, contrasts of resistivity and velocity or reflectivity.

Applications of gravity to mineral deposit environmental considerations includes identification of lithologies, structures, and, at times, orebodies themselves (Wright, 1981). Small anomalous bodies, such as underground workings, are not easily detected by gravity surveys unless they are at shallow depth.

MAGNETIC METHOD

The magnetic method exploits small variations in magnetic mineralogy (magnetic iron and iron-titanium oxide minerals, including magnetite, titanomagnetite, titanomaghemite, and titanohematite, and some iron sulfide minerals, including pyrrhotite and greigite) among rocks. Measurements are made using fluxgate, proton-precession,

Table 1. Summary of geophysical methods and their characteristics applicable to exploration and geoenvironmental studies.
[In method column: A, airborne surveys; B, borehole surveys; and G, ground surveys]

Method	Physical parameter measured	Typical units	Relevant physical property	Typical source of anomaly	Depth of investigation
Gravity: A,B,G	Total attraction of Earth's gravity field (the vertical attraction of anomalous masses) Gradient of Earth's gravity field	Milligals or gravity unit (0.1 mGal) Eötvös unit (10^{-9} gal/cm)	Density	Rock density contrasts	All
Magnetic: A,B,G	Vector component, or total attraction of Earth's magnetic field Gradient of Earth's magnetic field	Nanotesla, or gammas Nanotesla/m	Magnetic susceptibility and remanent magnetization "	Magnetic susceptibility and (or) remanent magnetization contrasts "	Surface to Curie isotherm
Gamma-ray scintillometry: A,B,G Gamma-ray Spectrometry: A,B,G	Rate of gamma-ray photons received Rate of gamma-ray photons received and their energy	Counts/second Counts/second in spectral regions. If calibrated, %K and PPM equiv. U and Th	Quantity of K+U+Th and daughters Quantity of K,U,Th and daughters	K+U+Th contrasts in Earth's upper 50 cm K,U, and Th contrasts in Earth's upper 50 cm	Upper 50 cm "
Seismic refraction: B,G Seismic reflection: B,G	Seismic energy travel time "	Meters, milliseconds "	Velocity of P or S waves "	Structures or velocity layer contrasts "	All "
Thermal bore-hole or shallow hole: B Thermal remote sensing: A,G	Thermal gradient or temperature Surface temperature day and night	Degrees C/m, degrees C Degrees C	Thermal conductivity Thermal inertia	Thermal flux or conductivity variations Thermal inertia contrasts	Hole depth About 5 cm
Electrical (see text) Direct current resistivity: B,G several variations in electrode geometry	Electrode position (m), applied current (A), and electric field (mV)	Meter, amps, millivolts; typically converted to units of resistivity (Ohm-m)	Resistivity	Lateral or vertical changes in resistivity	About 2 km
Electromagnetic methods (see text): A,B,G many variations available	Dependent on method; ratio of received to applied electric and magnetic fields	Impedance (Ohms) or dimensionless ratio; units of conductivity (Seimens/m) or resistivity (Ohm-m)	Conductivity (inverse of resistivity)	Lateral or vertical changes in Earth conductivity	Shallow (10 m; VLF; 100 m, controlled source), intermediate (1 km; AMT), deep (10 km; MT)
Mise-a-la-masse: B,G	Applied DC or low frequency AC field	Millivolts	Resistivity	Conductive body	A few hundred meters
Induced polarization: B,G	Resistivity change w/ frequency (PFE) Phase angle between transmitted and received signal(ϕ) Normalized area of part of received voltage decay curve	Percent change Milliradians Milliseconds	Interface ionic polarization	Metallic luster minerals and pore water Clay and zeolite minerals	About 2 km
Self potential: B,G	Natural near-static (direct current) electric field	Millivolts	Eh/pH electronic conductor; streaming potential and thermal coupling coefficients	Vertical change in Eh/pH caused by electronic conductor; ground water flow; thermal flux	A few hundred meters
Remote sensing: A	Reflected radiation intensity (UV, VIS, IR)	Recorded as optical or digital intensity image	Spectral reflectance, Albedo	Changes in spectral reflectance and Albedo	Surface only

Overhauser, and optical absorption magnetometers. In most cases, total-magnetic field data are acquired; vector measurements are made in some instances. Magnetic rocks contain various combinations of induced and remanent magnetization that perturb the Earth's primary field (Reynolds and others, 1990). The magnitudes of both induced and remanent magnetization depend on the quantity, composition, and size of magnetic-mineral grains.

Magnetic anomalies may be related to primary igneous or sedimentary processes that establish the magnetic mineralogy, or they may be related to secondary alteration that either introduces or removes magnetic minerals. In mineral exploration and its geoenvironmental considerations, the secondary effects in rocks that host ore deposits associated with hydrothermal systems are important (Hanna, 1969; Criss and Champion, 1984) and magnetic surveys may outline zones of fossil hydrothermal activity. Because rock alteration can effect a change in bulk density as well as magnetization, magnetic anomalies, when corrected for magnetization direction, sometimes coincide with gravity anomalies.

Magnetic exploration may directly detect some iron ore deposits (magnetite or banded iron formation), and magnetic methods often are useful for deducing subsurface lithology and structure that may indirectly aid identification of mineralized rock, patterns of effluent flow, and extent of permissive terranes and (or) favorable tracts for deposits beneath surficial cover. Geoenvironmental applications may also include identification of magnetic minerals associated with ore or waste rock from which hazardous materials may be released. Such associations permit the indirect identification of hazardous materials such as those present in many nickel-copper or serpentine-hosted asbestos deposits.

GAMMA-RAY METHODS

Gamma-ray methods (Durrance, 1986; Hoover and others, 1991) use scintillometry to identify the presence of the natural radioelements potassium, uranium, and thorium; multi-channel spectrometers can provide measures of individual radioelement abundances. Gamma-ray methods have had wide application in uranium exploration because they provide direct detection. Thorium is generally the most immobile of the three radioelements and has geochemical behavior similar to that of zirconium. Thorium content, like uranium content, tends to increase in felsic rocks and generally increases with alkalinity.

Gamma-ray spectrometry, because it can provide direct quantitative measures of the natural radioelements, provides geoenvironmental information concerning radiation dose and radon potential. Because uranium and (or) potassium are commonly enriched in or adjacent to some deposits, their presence may often be used to indirectly assess the potential for release of hazardous materials from ore or waste piles. Where sulfide minerals are present their oxidation accelerates uranium mobilization.

SEISMIC METHODS

Seismic techniques have had relatively limited utilization, due to their relatively high cost and the difficulty of acquiring and interpreting seismic data in strongly faulted and altered igneous terranes, in mineral assessments and exploration at the deposit scale. However, shallow seismic surveys employ less expensive sources and smaller surveys than are typical of regional surveys, and the cost of studying certain geoenvironmental problems in the near subsurface may not be prohibitive. Reflection seismic methods provide fine structural detail and refraction methods provide precise estimates of depth to lithologies of differing acoustic impedance. The refraction method has been used in mineral investigations to map low-velocity alluvial deposits such as those that may contain gold, tin, or sand and gravel. Applications in geoenvironmental work include studying the structure, thickness, and hydrology of tailings and extent of acid mine drainage around mineral deposits (Dave and others, 1986).

THERMAL METHODS

Two distinct techniques are included under thermal methods (table 1): (a) borehole or shallow probe methods for measuring thermal gradient, which is useful itself, and with a knowledge of the thermal conductivity provides a measure of heat flow, and (b) airborne or satellite-based measurements, which can be used to determine the Earth's surface temperature and thermal inertia of surficial materials, of thermal infrared radiation emitted at the Earth's surface. Thermal noise includes topography, variations in thermal conductivity, and intrinsic endothermic and exothermic sources.

Borehole thermal methods have been applied in geothermal exploration, but have seldom been used in mineral exploration. However, this method has potential usefulness in exploration and in geoenvironmental investigations (Ovnatanov and Tamrazyan, 1970; Brown and others, 1980; Zielinski and others, 1983; Houseman and others, 1989). Causes of heat flux anomalies include oxidizing sulfide minerals and high radioelement concentrations.

Conditions that may focus, or disperse, heat flow are hydrologic and topographic influences, as well as anomalous thermal conductivity. In geoenvironmental applications, oxidation of sulfide bodies in-place or on waste piles, if sufficiently rapid, can generate measurable thermal anomalies, which can provide a measure of the amount of metal being released to the environment. Borehole temperatures may also reflect hydrologic and hydrothermal systems that have exploration and geoenvironmental consequences. Airborne thermal infrared measurements have applications in geothermal exploration, and may have potential in mineral exploration and in geoenvironmental applications whenever ground surface temperature is anomalous due to sulfide oxidation, hydrologic conditions, or heat-flow perturbations due to structure or lithology (Strangway and Holmer, 1966).

Thermal infrared imaging methods are a specialized branch of more generalized remote sensing techniques. Images obtained in this wavelength range may be used for photogeologic interpretation or, if day and night images are available, to estimate the thermal inertia of the surface. Unconsolidated or glassy materials can be distinguished by their low thermal inertia. In places, thermal infrared images can distinguish areas of anomalous silicification (Watson and others, 1990).

ELECTRICAL METHODS

Electrical methods comprise a multiplicity of separate techniques that employ differing instruments and procedures, have variable exploration depth and lateral resolution, and are known by a large lexicon of names and acronyms describing techniques and their variants. Electrical methods can be described in five classes: (1) direct current resistivity, (2) electromagnetic, (3) mise-a-la-masse, (4) induced polarization, and (5) self potential. In spite of all the variants, measurements fundamentally are of the Earth's electrical impedance or relate to changes in impedance. Electrical methods have broad application to mineral and geoenvironmental problems: they may be used to identify sulfide minerals, are directly applicable to hydrologic investigations, and can be used to identify structures and lithologies.

Direct current resistivity method

Direct current resistivity methods measure Earth resistivity (the inverse of conductivity) using a direct or low frequency alternating current source. Rocks are electrically conductive as consequences of ionic migration in pore space water and more rarely, electronic conduction through metallic luster minerals. Because metallic luster minerals typically do not provide long continuous circuit paths for conduction in the host rock, bulk-rock resistivities are almost always controlled by water content and dissolved ionic species present. High porosity causes low resistivity in water-saturated rocks.

Direct current techniques have application to a variety of mineral exploration and geoenvironmental considerations related to various ore deposit types. Massive sulfide deposits are a direct low resistivity target, whereas clay alteration assemblages are an indirect low resistivity target within and around many hydrothermal systems. The wide range of earth material resistivities also makes the method applicable to identification of lithologies and structures that may control mineralization. Acid mine waste, because of high hydrogen ion mobility, provides a more conductive target than solutions containing equivalent concentrations of neutral salts.

Electromagnetic method

Electromagnetic measurements use alternating magnetic fields to induce measurable current in the Earth. The traditional application of electromagnetic methods in mineral exploration has been in the search for low-resistivity (high-conductivity) massive sulfide deposits. Airborne methods may be used to screen large areas and provide a multitude of targets for ground surveys. Electromagnetic methods, including airborne, are widely used to map lithologic and structural features (Palacky, 1986; Hoover and others, 1991) from which various mineral exploration and geoenvironmental inferences are possible.

Mise-a-la-masse method

The mise-a-la-masse method is a little used technique applied to conductive masses that have large resistivity contrasts with their enclosing host rock. In exploration, application of this method is principally in mapping massive sulfide deposits. This method is useful in geoenvironmental investigations of highly conductive targets; it has been applied to identify a contaminant plume emanating from an abandoned mine site (Osinsky and Donaldson, 1994).

Self potential method

Several possible natural sources generate measurable direct current or quasi-direct current, natural electrical fields

or self potentials. The association of a self potential anomaly with a sulfide deposit indicates a site of ongoing oxidation and that metals are being mobilized; other self potential anomalies are due to fluxes of water or heat through the Earth (Corwin, 1990). Geoenvironmental applications include searching for zones of oxidation and paths of ground water movement.

Induced polarization method

The induced polarization method provides a measure of polarizable minerals (metallic-luster sulfide minerals, clays, and zeolites) within water-bearing pore spaces of rocks. Polarizable minerals, in order to be detected, must present an active surface to pore water. Because induced polarization responses relate to active surface areas within rocks, disseminated sulfide minerals provide a much better target for this method than massive sulfide deposits, although in practice most massive sulfide deposits have significant gangue and have measurable induced polarization. Induced polarization has found its greatest application in exploration for disseminated sulfide ore, where it may detect as little as 0.5 volume percent total metallic luster sulfide minerals (Sumner, 1976). In geoenvironmental studies, induced polarization surveys are principally used to identify sulfide minerals, but it may have other applications, such as outlining clay aquitards that can control mine effluent flow.

REMOTE SENSING METHODS

Remote sensing includes methods that utilize images obtained in the ultra-violet, visible, and near infrared bands of the electromagnetic spectrum (table 1). Thermal infrared observations, discussed previously under thermal methods, are also part of remote sensing. Remote sensing data are treated in image format, often in digital form, so that they can be processed conveniently. By comparison with known spectral responses of minerals or mineral groups, iron hydroxide minerals, silica, clay alteration, etc., can be defined over broad areas. Remote sensing can be used in geoenvironmental studies to map surface alteration patterns (Knepper, 1989) and to identify anomalous vegetation patterns in areas related to abnormal metal content in soil (Birmie and Francica, 1981).

OTHER METHODS

A number of other geophysical or quasi-geophysical methods have been used, or have potential application, in mineral exploration. Application of these methods in geoenvironmental investigations has been limited, but should not be dismissed. Some peripheral techniques that have special uses (as in archeology), whose utilization is not widely known in mineral exploration, that may directly apply to shallow geoenvironmental investigations. Examples of such techniques are ground-penetrating radar (used to image the shallow subsurface in electrically resistive rock; Davis and Annan, 1992), the piezoelectric method (used in studies of quartz veins; Volarovich and Sobolev, 1969), ultraviolet laser induced fluorescence (the Luminex method, used to identify scheelite, hydrozincite, and other fluorescent minerals; Seigel and Robbins, 1983), airborne gas sniffing (used in mercury exploration), the Russian CHIM (partial extraction of metals) electrogeochemical sampling technique, and radon sensing.

GEOPHYSICAL INVESTIGATIONS IN GEOENVIRONMENTAL STUDIES

The major geoenvironmental concerns related to investigations described below include (1) identifying abandoned and concealed mine openings, (2) tracing toxic substances, including metals or radiative species released to air and (or) water, resulting from sulfide mineral oxidation, and (3) delineating geologic structures that control the flow of potentially toxic water. Geologic relations outline the surficial distribution and concentration of potentially toxic sources. Geophysical investigations can provide limited means to trace pollutants and their sources in the subsurface without drilling or opening shafts (King, 1993; Paterson, 1995). If drilling and mine shaft operations are permissible, an additional array of geologic, geochemical and geophysical surveys, including cross-hole tomography and in-shaft techniques, become available, but these are beyond the scope of this discussion.

Abandoned mine workings

Abandoned mine workings may be an environmental hazard because of the possibility of subsidence or collapse. They can also channel contaminated ground water flow, particularly if they are located in sulfide mineral-bearing rock and contain water. Several geophysical strategies enable identification of lost mine workings. In general, the deeper and smaller such workings are, the harder they are to locate using geophysical techniques. However, deep or small workings are less likely to collapse, so it may be less important to locate them. If abandoned workings contain metallic tram rails or ventilation tubes, it may be possible to trace such installations from the surface using a magnetometer or geoelectrical device. If part of the metallic installation is accessible, the mise-a-la-masse method

can be used to locate the rest of the installation. These methods only trace the metallic installation, so they will not identify workings where the installation is absent or, in the *mise-a-la-masse* method, where workings are disconnected from the energized installation segment. Further, the method may not map true voids; the tunnel where the metal was installed may have collapsed.

Magnetometers have been used to trace burned-out coal seams, particularly pyrite-bearing coal. During combustion, pyrite may oxidize to magnetite, which then can be traced using surface or airborne magnetic measurements. If the burned seam is still hot, geothermometry and infrared sensing methods may be used.

When the above special conditions are not met, the challenge for geophysical techniques is to find large voids, regardless of whether the voids are manmade. More reliable approaches to this challenge involve microgravity, seismic, ground-penetrating radar, geoelectric surveys, or a combination thereof. Microgravity requires measurements be made at a spacing about equal to the diameter of the workings being sought. Only shallow workings, whose tops are located at a depth less than about one opening-diameter, can be traced using microgravity.

Shallow, high-resolution seismic methods and ground penetrating radar have been used to trace caves. Both methods are applicable to identification of air- or water-filled openings. Jessop (1995) reports that ground penetrating radar returned massive, ringing reflections from the top of an air-filled cave buried about 6 m in sandstone. A large, but opposite polarity, ground penetrating radar response may result from water-filled caves; air and water filled caverns may be differentiated in this way. Ground penetrating radar signals, however, are attenuated by wet or clay soil, and are inefficient where these conditions exist in the surficial layer.

Geoelectrical work has also been successful in tracing cave systems. In the majority of reported cases, the caves were in resistive limestone strata. Direct current resistivity is particularly useful in identification of air-filled openings, though in some instances the caves were partly or completely filled with water. Electromagnetic methods, particularly at very low frequencies, are also efficient where cave floors are covered by conducting clay deposits. Guerin and Benderitter (1995) caution, however, that for caves in France that were traced, apparently successfully, using very low frequency techniques, the electromagnetic response was mainly generated by mud-filled fractures in the limestones rather than the caves themselves, which are localized along such fractures.

Contaminant plumes associated with sulfide deposits

Contaminant plumes, in sulfide-mineral-bearing environments, are intrinsically hazardous because they may merge with human water supplies or recreational water. *In situ* sulfide minerals near or above the water table may be actively oxidizing; the effect is likely to be greater in cases involving widely disseminated sulfide minerals because of greater surface area. Similarly, sulfide-mineral-bearing waste piles may oxidize when broken rock presents large surface area access for water and oxygen. Three geoelectrical techniques applicable to identification of sulfide-reduction/oxidation systems and their products are self potential, electromagnetic or direct current resistivity, and induced potential. In addition, ground penetrating radar may also detect the top of shallow acid water through relatively thin or resistive cover, and thermal studies have potential application in detecting oxidation centers and fluid circulation systems. Conductive materials that may cause uncertainties include clay, zeolites, sulfide minerals, and naturally saline water.

Self-potential applications: Self-potential investigations (Corwin, 1990) detect electrical potentials due to ongoing redox processes and involve measuring electrical potentials on grids of stations laid out on the surface or in boreholes. Self potential surveying is relatively inexpensive, and when used on closely spaced grids, accurately identifies redox cells in waste dumps. Self potential noise sources include electrical potentials generated by fluid movement, and natural potentials focused by topography.

Resistivity applications: Electromagnetic or direct current conductivity measurements may trace electrically conductive acid plumes (King and Pesowski, 1993). As these plumes are buffered, causing metal precipitation and neutralization of hydrogen ions, they become less conductive; resistivity surveys may be a useful monitoring method as well. Many different ground conductivity (or resistivity, the inverse of conductivity) measuring systems and survey approaches are available; each addresses different kinds of targets, target depths and dimensions, access considerations, and cultural interference problems, and has a unique range of interpretative difficulties. Conductivity data appropriate to local problems can often be collected and interpreted in rudimentary, rapid, and useful ways. Electrical conductivity maps can be useful for outlining contaminant plumes, but may also indicate anomaly highs caused by unrelated conductors (clays, for instance).

Induced polarization applications: Induced polarization is applied to detect disseminated conducting minerals, whether or not they are actively oxidizing. Flow channels carrying oxidizing fluids in high-sulfide-mineral tailings and waste dumps may have reduced induced polarization because of the formation of oxide minerals from sulfide minerals.

However, anomalies related to local sulfide mineral oxidation may be of low amplitude and difficult to resolve. Induced polarization is inefficient as an areal reconnaissance tool, but efficiently identifies disseminated mineral targets whose general location is already known. Advanced induced polarization equipment can discriminate between benign electrical conductors, like clays, and environmentally threatening ones, like heavy-metal plumes or petrochemical spills.

Other applications: Active oxidation of sulfide minerals may produce thermal anomalies that may be identified by infrared surveys or shallow heat-flow probes. Limited data are available concerning the use of thermal signatures in geoenvironmental investigations; thermal signatures may be low amplitude and overshadowed by topographic effects, thermal inertia contrasts in surrounding rocks, and heat distribution effects related to ground water circulation (Strangway and Holmer, 1966). Oxidized pyrrhotite within limited areas, for instance along fluid conduits in waste dumps, may be coincident with magnetic lows.

Argillic alteration

Argillic alteration that surrounds some sulfide deposits may be associated with resistivity lows, induced polarization highs, and moderate magnetic lows, whereas silicified rock and quartz lenses associated with sulfide deposits are associated with high resistivity, low magnetization, and increased density. Altered tracts commonly have diagnostic reflectance patterns on remote-sensing multispectral images. In addition, trace elements and alteration products may be absorbed by plants resulting in recognizable reflectance anomalies.

Thickness of waste piles

Tailings and waste pile thickness can be determined by direct current or electromagnetic resistivity soundings and seismic refraction and reflection. Uncertainties relate to the variability of waste pile properties and contrasts between waste material and country rock.

Structures controlling contaminated water flow

Numerous geologic structures that can focus ground water flow can be identified by various geophysical surveys. Aquitards can be identified by direct current or electromagnetic resistivity studies. Clay lenses are less resistive than sand- and gravel-bearing aquifers, unless contained pore water is ion rich or highly acidic, in which case the aquifers may be less resistive. Reflection seismic and ground penetrating radar may distinguish subtle velocity and resistivity changes related to distributions of aquifers and aquitards in sedimentary environments. Pore fluid with properties that vary laterally and with depth cause some uncertainties in aquitard delineation.

Lithologic boundaries and faults may be associated with porosity contrasts that may concentrate ground water flow. Porosity contrasts are associated with density, resistivity, and acoustic velocity contrasts, and some may have associated gamma-ray contrasts. In most cases, increased porosity lowers density and resistivity, the latter resulting from an increase of conductive pore fluid. In crystalline bedrock, faults and lithologic boundaries commonly have density and magnetic contrasts related to rock composition but ambiguities may result from subtle mineralogical changes in associated rocks.

Bedrock topography, including structural highs and buried channels, that influence ground water flow may contrast with overlying sedimentary and alluvial cover in having higher density, magnetization, and resistivity. These contrasts may be identified using gravity, resistivity, ground-penetrating radar, and seismic refraction and reflection. Anomalies may be small and ambiguities in defining bedrock topography or buried channels include equivalent amplitude anomalies from variable properties of both bedrock and overburden.

SUMMARY

Many geophysical methods commonly used in exploration have potential application to geoenvironmental investigations. Although these methods have mainly been used to identify pollutants and record their dispersion from mine areas, their application is not limited to studies of this sort. For instance, geophysical monitoring of pollutant activity, which requires significantly greater study, is another aspect of geoenvironmental investigations. Monitoring differs from detection chiefly in recurrent use of geophysical techniques. The effort required to extend application of geophysical techniques to naturally occurring pollutants related to mineralized, but unmined, rock or to other cultural concentrations of toxic or potentially toxic substances is minimal and could be of considerable assistance in meeting national needs for healthy environmental conditions (Henderson, 1992).

REFERENCES CITED

- Birmie, R.W., Francica, J.R., 1981, Remote detection of geobotanical anomalies related to porphyry copper mineralization: *Economic Geology*, v. 76, p.637-647.
- Brown, G.C., Cassidy, J. Oxburg, E.R., Plant, J., Sabine, P.A., and Watson, J.V., 1980, Basement heatflow and metalliferous mineralization in England and Wales: *Nature*, v. 288, p. 657-659.
- Corwin, R.F., 1990, The self-potential method for environmental and engineering applications, *in* Ward, S.W., *Geotechnical and environmental geophysics*, v.I: p. 127-145.
- Criss, R.E., and Champion, D.E., 1984, Magnetic properties of granitic rocks from the southern half of the Idaho batholith--Influences of hydrothermal alteration and implications for aeromagnetic interpretation: *Journal of Geophysical Research*, v. 89, no. B8, p. 7061-7076.
- Dave, N.K., Lim, T.P., Siwik, R., Blackport, R., 1986, Geophysical and biohydrogeochemical investigations of an inactive sulfide tailing basin, Noranda, Quebec, Canada. National Symposium on Mining, Hydrology, Sedimentology and Reclamation, University of Kentucky, Lexington, KY, Dec. 8-11, 1986, p.13-19.
- Davis, J.L., and Annan, A.P., 1992, Applications of ground penetrating radar to mining, groundwater, and geotechnical projects: selected case histories, *in* Pilon, J., ed., *Ground penetrating radar*, Geological Survey of Canada, Paper 90-4, p.49-55.
- Durrance, E.M., 1986, *Radioactivity in geology, principles and applications*: Ellis Horwood Ltd., 441 p.
- Guerin, Roger, and Benderitter, Yves, 1995, Shallow karst exploration using MT-VLF and DC resistivity methods: *Geophysical Prospecting*, v. 43, no. 5, p. 635-654.
- Hanna, W.F., 1969, Negative aeromagnetic anomalies over mineralized areas of the Boulder batholith, Montana: U.S. Geological Survey Professional Paper 650-D, p. 159-167.
- Henderson, R.J., 1992, Urban geophysics-a review: *Exploration Geophysics*, v. 123, p. 531-542.
- Hoover, D.B., Grauch, V.J.S., Pitkin, J.A., Krohn, D., and Pierce, H.A., 1991, Getchell trend airborne geophysics-an integrated airborne geophysical study along the Getchell trend of gold deposits, North-Central Nevada, *in* Raines, G.L., Lisk, R.E., Schafer, R.W., and Wilkinson, W.H., eds., *Geology and Ore Deposits of the Great Basin*, Geological Society of Nevada, v. 2, p. 739-758.
- Hoover, D.B., Heran, W.D., and Hill, P.L., eds., 1992, *The geophysical expression of selected mineral deposit models*: U.S. Geological Survey Open-file Report 92-557, 129 p.
- Houseman, G.A., Cull, J.P., Muir, P.M., and Paterson, H.L., 1989, Geothermal signatures and uranium ore deposits on the Stuart Shelf of South Australia: *Geophysics*, v. 54, p. 158-170.
- Jessop, James A., Hauser, K.L., and Gese, D.D., 1995, Evaluation of geophysical methods for locating subsurface hazards in the Shawnee National Forest: DoI Conference on the Environment and Safety, Colorado Springs CO, April 24-28, 1995; Abstract Book, p. 26.
- Knepper, D.H., 1989, Mapping hydrothermal alteration with Landsat thematic mapper data, *in* Lee and others, eds., *Mineral deposits of North America*, v. 1, Remote sensing in exploration geology, Field trips for the 29th International Geological Congress: Washington, DC, American Geophysical Union, p. 13-21.
- King, A., and Pesowski, M., 1993, Environmental applications of surface and airborne geophysics in mining: *Canadian Institute of Mining and Metallurgy Bulletin*, v. 86, p. 58-67.
- Mwenifumbo, C.M., 1993, Borehole geophysics in environmental application: *Canadian Institute of Mining and Metallurgy Bulletin*, v. 86, no. 966, p. 43-49.
- Osiensky, I.L., and Donaldson, P.R., 1994, A modified mise-a-la-masse method for contaminant plume delineation: *Ground Water*, v. 32, no. 3, p. 448-457.
- Ovnatanov, S.T., and Tamrazyan, G.P., 1970, Thermal studies in subsurface structural investigations, Aspheron Peninsula, Azerbaijan USSR: *American Association of Petroleum Geologists Bulletin*, v. 54, p. 1677-1685.
- Palacky, G.J., 1986, Airborne resistivity mapping, *in* Palacky, G.J., ed., *Geological Survey of Canada paper 86-22*, 195 p.
- Paterson, Norman, 1995, Application of geophysical methods to the detection and monitoring of acid mine drainage, *in* Bell, R.S., ed., *Proceedings of the Symposium on the application of geophysics to engineering and environmental problems*, Orlando, Florida, April 23-26, Environmental and Engineering Geophysical Society, p. 181-189.
- Reynolds, R.L., Rosenbaum, J.G., Hudson, M.R., and Fishman, N.S., 1990, Rock magnetism, the distribution of magnetic minerals in the Earth's crust, and aeromagnetic anomalies, *in* Hanna, W.F., ed., *Geologic Applications of Modern Aeromagnetic Surveys*: U.S. Geological Survey Bulletin 1924, p. 24-45.
- Seigel, H.S., and Robbins, J.C., 1983, Exploring with Luminex: *Mining Engineering*, v. 35, p. 729-732.

- Society of Exploration Geophysicists, 1966, (1967), *Mining Geophysics*, v. 1, Case Histories; v. 2, Theory: Tulsa, Society of Exploration Geophysicists, 492 p. (v. 1); 708 p., (v. 2).
- _____ 1990, *Geotechnical and environmental geophysics*, v. 1, Review and Tutorial; v. 2, Environmental and Groundwater, *in* Ward, S.H., ed., Tulsa, Society of Exploration Geophysicists, 389 p., (v. 1); 343 p., (v. 2).
- Strangway, D.W., and Holmer, R.C., 1966, The search for ore deposits using thermal radiation: *Geophysics*, v.31, no. 1, p. 225-242.
- Sumner, J.S., 1976, *Principles of induced polarization for geophysical exploration*: Elsevier, 277 p.
- Van Blaricom, Richard, 1980, *Practical geophysics*: Northwest Mining Association, 303 p.
- Volarovich, M.P., and Sobolev, G.A., 1969, Direct piezoelectric prospecting of quartz and pegmatitic veins: *Geoexploration*, v. 7, no. 4, p. 241-246.
- Watson, Kenneth, Kruse, F.A., and Hummer-Miller, Susanne, 1990, Thermal infrared exploration in the Carlin trend, northern Nevada: *Geophysics*, v. 55, no. 1, p. 70-79.
- Wright, P.M., 1981, Gravity and magnetic methods in mineral exploration, *in* Skinner, B.J., ed., *Economic Geology*, 75th Anniversary volume, p. 829-839.
- Zielinski, G.W., and DeCoursey, G.M, 1983, Localized heat flow and Tertiary mineralization in southern New Mexico: *Geophysics*, v. 48, p. 1212-1218.

MAGMATIC SULFIDE DEPOSITS

(MODELS 1, 2b, 5a, 5b, 6a, 6b, and 7a; Page, 1986a-g)

by Michael P. Foose, Michael L. Zientek, and Douglas P. Klein

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Magmatic sulfide deposits are sulfide mineral concentrations in mafic and ultramafic rocks derived from immiscible sulfide liquids. A number of schemes exist for subdividing these deposits. Most are based on the tectonic setting and petrologic characteristics of the mafic and ultramafic rocks (Page and others, 1982; Naldrett, 1989), or on the spatial association of mineralized rock with enclosing ultramafic and mafic host rocks (stratabound, discordant, marginal, and other; Hulbert and others, 1988). Page (1986a-g) presented discussions of several different subtypes based, in part, on both these approaches (Models 1, 2b, 5a, 5b, 6a, 6b, and 7a). However, these deposits are similar enough that they can be treated as a group with regard to their geoenvironmental manifestations.

The similarity of these deposits result, in part, from similar genesis. Exsolution of immiscible sulfide liquids from mafic-to-ultramafic magmas is the fundamental process that forms magmatic sulfide deposits. Once formed, droplets of immiscible sulfide liquid settle through less dense silicate magma. The sulfide liquid acts as a "collector" for cobalt, copper, nickel, and platinum-group elements (PGE) because these elements are preferentially concentrated in sulfide liquids at levels 10 to 100,000 times those in silicate liquids. To a lesser degree, iron is also preferentially partitioned into the sulfide liquid and, because of its greater abundance, most immiscible sulfide liquid is iron-rich.

The combination of physically concentrating dense sulfide liquid and chemically concentrating elements in the sulfide liquid is responsible for forming most economically minable, magmatic-sulfide deposits. Magmatic sulfide ore is typically associated with: (1) abrupt variations in the cumulus-mineral succession, including major lithologic changes, reversals or changes in crystallization order, discontinuities in mineral fractionation patterns and cyclic units, (2) rocks near the lower contact of an intrusion that may contain country rock xenoliths and may be characterized by irregular variations in grain size, mineralogy, and texture, (3) rocks near the base of a flow, or (4) pegmatoids and rocks enriched in minerals that crystallize late from silicate magmas. However, for the purposes of developing a geoenvironmental model for this group of deposits, the principal variables are the composition of the host rocks, the abundance and types of sulfide minerals, and (to a much lesser extent) sulfide mineral composition. General characteristics for the deposit subtypes described by Page (1986a-g) are listed in table 1.

Examples

Magmatic sulfide minerals concentrated near the margins of intrusions:

Stillwater nickel-copper (Model 1)-Mouat deposit, Stillwater Complex, Mont. (Zientek, 1993); Vaaralampi deposit, Suhanho-Konttijarvi intrusion, Finland (Alapieti and others, 1989)

Duluth Cu-Ni-PGE (Model 5a)-Dunka Road deposit, Duluth Complex, Minn.; Great Lakes nickel deposit, Crystal Lake Gabbro, Ontario, Canada (Eckstrand and others, 1989)

Synorogenic-synvolcanic Ni-Cu (Model 7a)-Brady Glacier deposit, La Perouse Intrusion, Alaska; Big Indian Pond, Moxie intrusion, Maine

Noril'sk Cu-Ni-PGE (Model 5b)-Medvezhy Creek deposit, Noril'sk and Oktybr'sky deposit, Talnakh; Russia Impact-related intrusions-Sudbury Complex, Canada

Stratiform concentrations of disseminated magmatic sulfide minerals in layered intrusions:

Merensky Reef PGE (Model 2b)-Merensky Reef, Bushveld Complex, Republic of South Africa (Naldrett and others, 1987); J-M Reef, Stillwater Complex, Mont. (Todd and others, 1982)

Magmatic sulfide mineral and PGE concentrations at or below impermeable layers:

No model-Picket Pin deposit, Stillwater Complex, Mont. (Boudreau and McCallum, 1986)

Pegmatoidal lenses, pipes, and other discordant mineralization:

No model-Vlakkfontein nickel pipes, Bushveld Complex, Republic of South Africa (Vermaak, 1976); Janet 50 zone, Stillwater Complex, Mont. (Volborth and Housley, 1984)

Magmatic sulfide minerals concentrated in ultramafic volcanic rocks:

Komatiitic Ni-Cu (Model 6a)-Kambalda deposits, Australia

Dunitic Ni-Cu (Model 6b)-Mount Keith deposit, Australia

Magmatic sulfide minerals concentrated in ultramafic cumulates in ophiolite complexes:

No model-Acoje, Philippines; Kraste, Albania

Table 1. General features of different magmatic sulfide deposit types. (Model numbers from Page, 1986a-g)

Deposit Type	Model no.	General description	Sulfide mineral abundance	Sulfide mineral composition	Size	Host rock
Still-water Ni-Cu	1	Disseminated to massive sulfide concentrations in mafic and ultramafic rocks at the base of large layered intrusions	Disseminated to massive	Fe>Ni>Cu	Small pods to large deposits that may exceed 100 million tons	Ultramafic and mafic
Meren-sky Reef	2b	Thin (1-5 m) disseminations of sparse (1-5 percent) sulfide minerals in mafic (gabbroic and troctolitic) rocks within the main body of large, layered intrusions	Disseminated	Fe-Ni-Cu PGE	Thin zones that may extend laterally for over 100 km. Individual mines within these zones often report reserves greater than 100 million tons	Mafic
Duluth Cu-Ni-PGE	5a	Disseminated to massive concentrations in mafic to ultramafic rocks in the basal parts of rift-related intrusions	Mostly disseminated, some massive	Fe>Cu>Ni	Small massive pods to disseminated bodies containing as much as several hundred million tons of ore	Mostly mafic, lesser ultramafic
Noril'sk Cu-Ni-PGE	5b	Disseminated sulfide in lower third, and massive sulfide near base of complex, subvolcanic, elongate intrusions less than 350 m thick	Extensive disseminated and massive ore	Fe>Cu>Ni>PGE	Disseminated deposits tens of meters thick over entire area of intrusion; Massive sulfide orebodies as much as 45 m thick and 2.5 km ² in area	Mafic, ultramafic, and meta-sedimentary
Komatiitic Ni-Cu	6a	Mostly massive, lesser disseminated, sulfide deposits at the base of Archean or Proterozoic ultramafic, komatiitic flows	Mostly massive, minor disseminated	Fe>Ni	Generally deposits less than 2 million tons; median size is 1.6 million tons	Ultramafic
Dunitic Ni Cu	6b	Disseminated sulfide deposits within Archean or Proterozoic komatiites	Disseminated	Fe>Ni	Large low grade deposits with median size about 30 million tons	Ultramafic
Syn-orogenic-syn-volcanic Ni-Cu	7a	Disseminated to massive sulfide deposits in the basal parts of mafic to ultramafic intrusions that where emplaced during orogenesis	Disseminated to massive	Fe>Cu>Ni	Generally fairly small, median size of about 2 million tons	Mostly mafic, lesser ultramafic

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include asbestos (Model 8d); soapstone; greenstone gold (Model 36a); Bushveld chromite (Model 2a); podiform chromite (Model 8a), Bushveld iron-titanium-vanadium (Model 3), platinum group element placer (Model 39a), nickel laterite (Model 38a).

Potential environmental considerations

- (1) Mining exposes sulfide minerals that have significant acid generating potential.
- (2) Metals associated with sulfide (particularly iron sulfide) ore may contaminate ground and surface water.
- (3) Some deposits are extremely large and development may involve ground disturbance throughout large areas.
- (4) Sulfur dioxide may be vented to the atmosphere during sulfide ore smelting; downwind acid and toxic metal

abundances may be enhanced.

(5) Significant amounts of sulfide-mineral-bearing tailings and slag are produced; these must be isolated from surface and ground water.

Many magmatic sulfide deposits are quite large or form groups that define large mining districts. Past mining of some of these deposits or districts has produced some well-known examples of severe environmental impact. The impact associated with mining in the Sudbury district (Canada) is probably the best documented; the severe environmental degradation associated with the Noril'sk district (Russia) is less well known. However, implementation of new pollution-control techniques and aggressive efforts at environmental remediation have substantially improved the environment around the Sudbury district. Recently permitted and currently ongoing mining of the palladium-platinum deposit in the Stillwater Complex, Mont., demonstrates that operations extracting ore from these deposits can meet the most rigorous modern environmental standards.

Exploration geophysics

Interconnected sulfide minerals produce electrically conductive zones that can be located with induced polarization, electromagnetic, and magneto-telluric surveys. Some of these deposits may be identified by magnetic surveys because they may contain abundant magnetite. Magnetite is also abundant in most mafic host rocks and may indicate regional targets or be a source of "noise" in mineral exploration. Large sulfide mineral masses may be located by seismic refraction. Sulfide-mineral concentrations and their mafic and ultramafic host rocks may be associated with mass excesses that can be identified by gravity surveys. Remote sensing may help identify areas in which ore is present. In particular, band ratioing can be used to identify gossans; more generally, images can be used to identify geologic settings that are favorable for the concentration of ore.

References

Naldrett (1979, 1981, 1989), Lightfoot and Naldrett (1994).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Deposit size ranges widely (table 1).

Host rocks

Host rocks are predominantly mafic to ultramafic igneous rocks. Occasionally significant ore is in footwall country rocks of diverse metasedimentary or meta-igneous origin and composition.

Surrounding geologic terrane

Deposits are in diverse geologic settings, including (1) deformed greenstone belts and calc-alkaline batholiths associated with convergent plate margins, (2) ophiolite complexes that formed at constructive plate margins, (3) intraplate magmatic provinces associated with flood-basalt type magmatism, and (4) passively rifted, continental margins.

Wall-rock alteration

Hydrothermal alteration related to ore-forming processes is generally not significant for magmatic sulfide deposits. Many deposits and host rocks have experienced varying amounts of alteration either as a result of deuteritic processes, metamorphism, or weathering. Primary silicate mineralogy consists of varying proportions of calcic plagioclase, orthopyroxene, clinopyroxene, and olivine. Brown amphibole and biotite may be minor accessory phases. Trace amounts of quartz, apatite, and potassium feldspar may be present. In most cases, alteration involves development of hydrous phases. Systematic alteration zoning may be developed adjacent to faults or fractures that focus fluid flow. Olivine is the phase most likely to be altered; alteration of plagioclase and pyroxene is somewhat less likely. Olivine is typically altered to serpentine minerals, magnetite, and minor calcite. Plagioclase is altered to epidote, clay minerals, sericite, and calcite. Pyroxenes are altered to actinolite/tremolite, serpentine, talc, and chlorite. Biotite is altered to chlorite.

Nature of ore

Sulfide minerals may be concentrated in structurally low areas at the base of intrusions or flows (fig. 1) or may be in zones where silicate magma interacted with xenoliths. Sulfide mineral concentrations in layered, cumulate

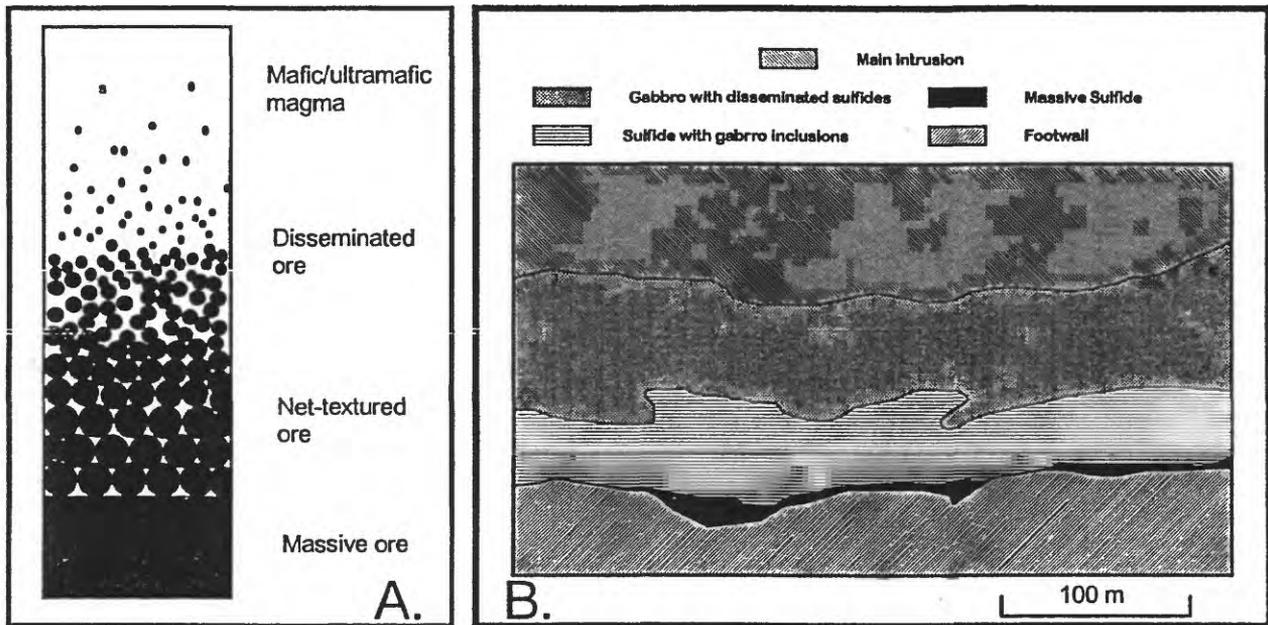


Figure 1. A, Schematic section of a magmatic sulfide deposit showing the vertical gradation downward from disseminated to massive ore. B, Generalized map showing massive sulfide mineral concentrations in footwall embayments of the Sudbury Complex (Canada).

sequences may be related to major lithologic features such as cyclic-unit boundaries, unconformities, chromite seams, pegmatoids, or stratigraphic intervals characterized by major changes or discontinuities in cumulus minerals.

Deformation and alteration can remobilize sulfide minerals into breccia ore and segregate sulfide minerals into fractures, cleavage planes, and veins. Remobilized sulfide-mineral assemblages may be copper-rich relative to sulfide mineral assemblages that are not remobilized. Sulfide-mineral assemblages that appear to have precipitated from fluids moving through fault zones or along joint surfaces are dominated by pyrite.

Deposit trace element geochemistry

Primary abundance variations of nickel, copper, and platinum group elements in magmatic-sulfide ore are controlled by the composition of the silicate magma and the mass ratio of silicate to sulfide liquid (Naldrett, 1989). In addition to sulfur, iron, nickel, copper, cobalt, and the platinum group elements (platinum, palladium, rhodium, ruthenium, iridium, and osmium), these sulfide minerals may contain minor Ag, As, Au, Bi, Hg, Pb, Sb, Se, Te, and Zn. Compositions of immiscible sulfide liquids are also affected by fractional crystallization of the host magma, which affects the concentrations of metals in the magma, and oxygen fugacity, which affects partition coefficients. Fractional crystallization of sulfide melt may result in sulfide mineral cumulates that are enriched in iron, cobalt, iridium, ruthenium, and rhodium and a residuum that is enriched in copper, palladium, platinum, gold, and other minor elements, including arsenic, bismuth, tellurium, and antimony (Naldrett, 1989; Zientek and others, 1990). Subsolidus equilibration of sulfide minerals with the enclosing silicate-rich or oxide-rich rock may modify bulk compositions of the sulfide-mineral assemblages Naldrett (1989); the greatest change occurs for small (tens of microns), scarce sulfide mineral inclusions in silicate or oxide minerals.

Three additional geologic factors control ore composition. First is the ratio of silicate host rock (mostly olivine, pyroxene, and plagioclase) to sulfide minerals. Silicate minerals are gangue that dilutes ore; as silicate abundance increases, ore grade decreases. Second is the composition of the magma from which the sulfide minerals separated. Ultramafic magmas produce sulfide ore with higher nickel-copper ratios than mafic magmas. Third is the relative abundance of the original immiscible sulfide liquid. Separation of relatively large amounts of immiscible sulfide liquid causes large amounts of iron to be extracted from the silicate magma, in addition to removal of less abundant nickel, copper, and platinum-group elements. Such ore is usually iron rich, but has low nickel, copper, and platinum-group element grades. Representative compositions of ore from several different deposits are shown in tables 2 and 3. Compositions in table 2 are recalculated to 100 percent sulfide minerals; silicate gangue causes measured ore grades to be significantly lower. Detailed mineralogic studies show that magmatic sulfide minerals (primarily pyrrhotite, pentlandite, and chalcopyrite) from the Noril'sk district, Russia, contain trace metals in the

Table 2. Representative major element compositions from some magmatic sulfide deposits normalized to 100 percent sulfides (after Naldrett, 1989).

[Ni, Cu, and Co weight percent; Pt and Pd, ppb. ---, no data]

Deposit/ magma type	Ni	Cu	Co	Pt	Pd
Langmuir/ ultramafic	14.6	.67	.27	890	1,600
Katiniq/ ultramafic	10.5	3.7	.23	4,130	15,530
Merensky Reef/ mafic	10.9	4.65	---	279,000	120,000
Falconbridge/ mafic	5.35	1.52	.17	2,130	3,170
Noril'sk/ mafic	9.0	10.8	---	18,000	47,000
Minnimax/ mafic	3.91	17.2	.37	2,640	8,840

Table 3. Representative trace element compositions of magmatic ore.

[Sulfur, weight percent; all others, ppm]

Deposit	S	Pd	Pt	Te	Bi	As	Sb	Hg	Sn
J-M Reef ¹	<0.01 1.64	0.38 182	0.33 51.6	0.03 17	<0.01 20	0.18 16.2	<0.05 1	<0.01 0.16	0.3 1.3
MSZ ²	0.36 2.8	0.088 3.1	0.26 6.1	0.35 4.8	0.62 5.8	0.42 2.2	<0.05 0.22	<0.01 0.38	0.30 0.60
Noril'sk- Talnakh Cu-poor ³	1.46 37	1.65 63	0.42 64	1 11	0.32 3.3	-- --	0.15 0.96	-- --	1.1 9.8
Noril'sk- Talnakh Cu-rich ³	31.9 34	140 583	41.8 --	22 210	5.5 42	-- --	0.285 4.85	-- --	15.7 84.5

¹ Median values of drill core from 3800 W stope of Stillwater Mine, J-M Reef (Zientek and others, 1990). Maximum values in second row.

² Median values of two intercepts through the Main Sulfide Zone, Great Dyke, Zimbabwe (Zientek and Wilson, unpub. data). Maximum values in second row.

³ Median values of all ore samples, Noril'sk Talnakh district (Zientek, unpub. data). Maximum values in second row.

approximate ranges of 60 to 650 ppm zinc, 130 to 390 ppm selenium, 11 to 210 ppm silver, 8 to 35 ppm cadmium, 15 to 35 ppm tin, 19 to 390 ppm tellurium, 150 to 690 ppm lead, and as much as 60 ppm gallium and 30 ppm indium (Czamanske and others, 1992).

Ore and gangue mineralogy and zonation

Sulfide-mineral ore assemblages, dominated by pyrrhotite, pentlandite, and chalcopyrite, result from solid-state recrystallization of high-temperature sulfide minerals. These three minerals are the principal acid generating phases in magmatic sulfide deposits and their proportions are determined by the initial bulk composition of the immiscible sulfide liquid. The sulfide mineral content of these ore deposits varies from less than ten to more than sixty percent.

Magnetite is commonly intergrown with the sulfide minerals. Minor phases include platinum-group-element minerals (sulfide, arsenide, telluride, antimonide, and alloy minerals), nickel- and cobalt-bearing arsenide minerals (for example gersdorffite), galena, sphalerite, and gold, silver, and lead telluride minerals.

Gangue mineralogy is the same as that of the host and consists primarily of plagioclase, orthopyroxene, clinopyroxene, and olivine. Minor, secondary phases include serpentine minerals, talc, magnetite, calcite, epidote, sericite, actinolite, chlorite, tremolite, and clay minerals.

Mineral characteristics

The mineralogy and textures of sulfide ore record a prolonged and complex process starting with solidification of the sulfide liquid, either as an iron-nickel-rich or an iron-copper-rich solid solution and continuing solid-state transformation and recrystallization; these textures can be substantially modified by alteration and weathering. Iron, nickel, and copper phases are commonly intimately intergrown.

When not modified by weathering or alteration, the textures of silicate and sulfide minerals record the distribution and abundance of the sulfide liquids and the interaction between solid silicate minerals and molten sulfide liquid. In rocks with less than 10 volume percent sulfide minerals (disseminated ore), sulfide minerals form fine (<1 mm)- to coarse-grained (>5 mm) droplet-shaped aggregates that are molded around and interstitial to the cumulus or earlier-formed silicate minerals or may be present as fine-grained, rounded aggregates enclosed in cumulus minerals. In rocks containing 10 to 60 volume percent sulfide minerals (matrix ore), aggregates of sulfide minerals are interstitial to earlier-formed silicate minerals but are interconnected. In rocks with more than 60 volume percent sulfide minerals (massive ore), sulfide minerals form the matrix of the rock.

The bulk sulfur content of sulfide-mineral aggregates is between 34 and 40 weight percent; the remaining 60 to 66 weight percent is mostly iron, plus copper and nickel. Consequently, the molecular-metal-sulfur ratio of magmatic sulfide minerals is relatively constant at about 1:1. In contrast, pyrite has a metal-sulfur ratio of 1:2. Therefore, magmatic sulfide ore has a much more restricted acid-generating capacity than ore that contains substantial pyrite.

Secondary mineralogy

Minerals that may form during alteration and weathering of sulfide minerals include violarite, bornite, mackinawite, cubanite, pyrite, marcasite, troilite, vaesite, smythite, polydymite, millerite, hematite, and magnetite. In supergene environments, chalcocite, malachite, native copper, cuprite, nickel-iron carbonate, nickel- and nickel-iron hydroxycarbonate, and nickel-silicate minerals may form. Gossans commonly form above sulfide-rich rocks.

Topography, physiography

Magmatic-sulfide deposits do not have diagnostic topographic or physiographic characteristics.

Hydrology

Many deposits form stratiform sheets and lenses, near the bottoms of intrusions or flows, that could localize ground water flow. However, no known consistent relation between magmatic sulfide ore and hydrologic controls are known.

Mining and milling methods

These deposits have been and are being mined both by underground and by open-pit methods. Underground mining is currently in progress at platinum-group-element deposits of the Stillwater, Mont., and Bushveld, South Africa, complexes and the komatiite-hosted nickel deposits in the Kambalda, Australia, district. Deposits being mined both by open pit and underground methods include those in the Sudbury Complex, Canada, the Manitoba, Canada, nickel belt, and the Noril'sk-Talnakh, Russia, district. Subsequent to mining, most ore is ground and concentrated by flotation, gravity, or magnetic methods to form either a bulk sulfide mineral concentrate or separate copper- and nickel-rich concentrates. Pyrrhotite-rich (iron-rich) concentrates at Noril'sk are being stored for later processing. Gravity concentrates may be sent directly to refineries, but most ore is smelted to separate iron-rich slag from nickel- and copper-rich matte. This matte is then refined by a variety of processes to extract nickel, copper, and platinum group elements. Pyrrhotite-rich concentrates may be treated by hydrometallurgical techniques.

Table 4. Composition of drainage water associated with Duluth and Stillwater Complex sulfide deposits (SCS Engineers, 1984; Feltis and Litke, 1987; Ritchie, 1988). Data in $\mu\text{g/l}$; --, no data.

	pH	Cu	Ni	Co	Zn
Duluth	6.4-7.7	1,800	40,000	2,400	2,400
Duluth	4.5-6.8	22,000	38,000	--	--
Duluth	6.4-7.1	900	9,000	900	200
Duluth	7.2	53	2,420	21	40
Stillwater	7.9	32	180	--	<3

ENVIRONMENTAL SIGNATURES

Drainage signatures

Studies show that the aqueous concentrations of nickel, copper, iron, and cobalt are largely controlled by their absorption on hydrous oxide minerals of iron and manganese (Richter and Theis, 1980). Estimates indicate that of the nickel transported by major rivers, 0.5 percent is in solution, 3.1 percent is adsorbed, 47 percent forms precipitated coatings, 14.9 percent is in organic matter, and 34.4 percent is crystalline material (Snodgrass, 1980; Nriagu, 1980). Only about 1 percent of copper in surface water is transported in a soluble form, while about 85 percent is moved as particulate crystalline phases, 6 percent is bound to metal hydroxide coatings on particles, 5 percent is associated with organic material, and 3 percent is adsorbed onto suspended particles (Nriagu, 1979).

Some of the limited data available for water draining unmined and mined deposits associated with mafic or ultramafic rocks are presented in table 4. The data include analyses of water that drains naturally exposed sulfide minerals at the base of the Stillwater, Mont., Complex and that from four different mining sites in the Duluth, Minn., Complex. The data from table 4 are plotted on a "Ficklin" diagram (fig. 2). Despite the fact that this water was analyzed for only a few of the metals typically reported on this plot, the analyses show quite high metal concentrations, especially for water that has a relatively neutral pH.

Additional information indicates that water discharged from some bulk-ore sample sites in the Duluth Complex contains nickel, copper, cobalt, and zinc abundances as much as 400 times baseline abundances (Eger and Lapakko, 1989); one study reports as much as 700 $\mu\text{g/l}$ copper and nickel in contaminated water, whereas adjacent ground water contained less than 25 $\mu\text{g/l}$ metal (Siegel and Ericson, 1980). Best- and worse-case water quality estimates were made for emissions from test pits and ore stockpiles as part of a regional environmental study. Estimates for the combined abundances of copper, nickel, cobalt, and zinc were between 107 and 6,610 $\mu\text{g/l}$ for

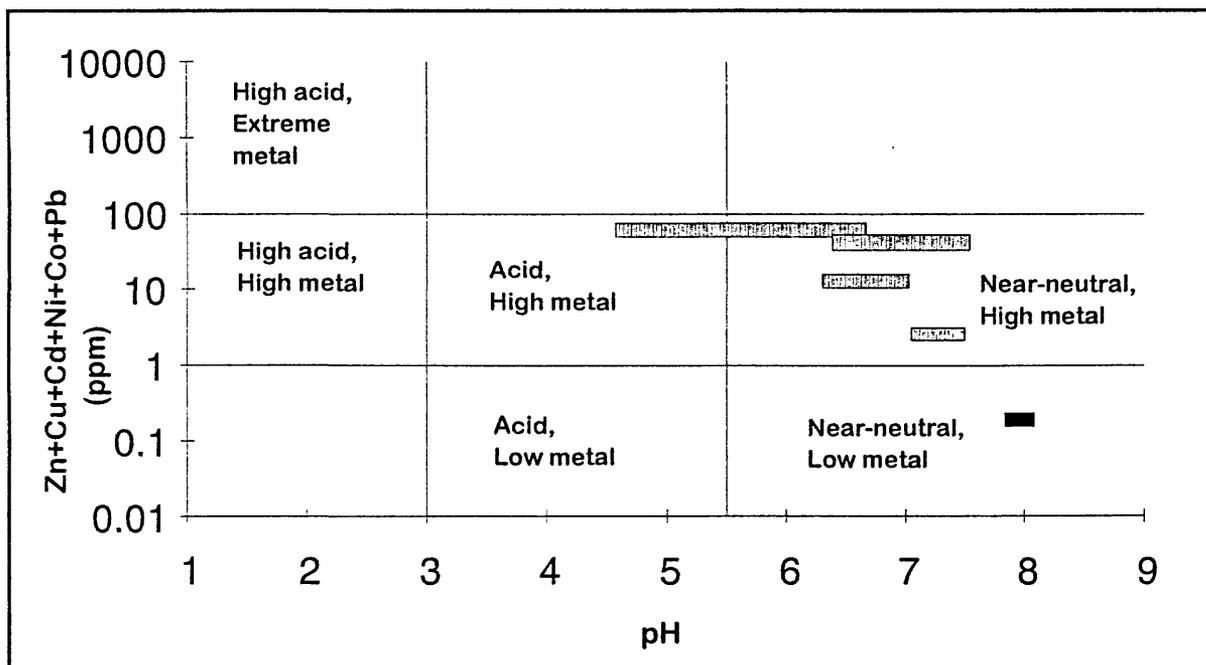


Figure 2. Plot of partial water analyses from the Duluth complex (striped) and Stillwater complex (solid).

discharges from tailings basins, 2,534 to 46,310 $\mu\text{g/l}$ for emissions from ore stock piles, and 125 to 46,840 $\mu\text{g/l}$ for mine water (Ritchie, 1988). "Mine water" used to simulate environmental effects related to the Duluth Complex in remediation studies has a pH of 4.5 and contains 2,000 $\mu\text{g/l}$ sulfate and between 50 and 1,000 $\mu\text{g/l}$ nickel (Hammack and Edenborn, 1992). Laboratory study of Duluth Complex ore (Lapakko and Antonson, 1994) has demonstrated a direct correlation between ore sulfur content and pH of associated drainage water. Drainage water associated with ore that contains 0.18 to 0.4 weight percent sulfur has a pH of 6.1, water associated with ore that contains 0.41 to 0.71 weight percent sulfur has a pH between 4.8 and 5.3, and water associated with ore that contains 1.12 to 1.64 weight percent sulfur has a pH between 4.3 and 4.9. Finally, a study of Sudbury ore from the Nickel Rim nickel-copper tailings impoundment demonstrates a well-developed vertical gradient within tailings water compositions. Water draining the uppermost part of the tailings has low pH (2.1 to 3.5), whereas that draining the basal part of the tailings, where acid-consuming minerals are more abundant, has a pH of about 6.5. The nickel abundance of tailings water is sensitive to pH; nickel abundances change from 250,000 $\mu\text{g/l}$ to less than 10,000 $\mu\text{g/l}$ as pH increases from 4.5 to greater than 5.8 (Blowes and Ptacek, 1994).

Metal mobility from solid mine wastes

Magmatic sulfide deposits may contain widely variable amounts of sulfide minerals. As a generalization, deposits may be separated into two groups. Platinum-group-element-rich deposits in large, layered intrusions tend to have low sulfide mineral abundances (1 to 5 weight percent) and low total-metal abundances. Consequently, they have a relatively restricted capacity to generate significant amounts of acidic and (or) metal-enriched drainage. Most of the other economically extractable magmatic-sulfide deposits contain substantial amounts of sulfide minerals (most greater than 15 weight percent, many exceeding 40 weight percent) and large metal abundances. They have significantly greater potential for generating acid and (or) metal-enriched drainage.

The limited data summarized in figure 2 are for deposits with high sulfide mineral concentrations. Mine water may contain high concentrations of metals, even when pH is near neutral. The relatively high pH of this water may reflect both the relatively restricted acid generating capacity of these sulfide minerals as compared to ore having lower metal-sulfur ratios and the acid buffering capability of mafic and ultramafic host rocks.

Kwong (1993) shows that acid generation capacity is directly proportional to both the metal-sulfur atomic ratio and to the proportion of ferrous iron in the sulfide phases. Pyrite, with its 1:2 metal-sulfur ratio, for example, has a much greater acid generating capacity than most magmatic sulfide ore, which has a metal-sulfur ratio of approximately 1. Non-iron-bearing phases with metal-sulfur ratios ≥ 1 do not generate acid. Further, calcic plagioclase and olivine present in the host rocks of most magmatic sulfide deposits are fast-weathering and fairly reactive minerals (Kwong, 1993). Consequently, both mafic and ultramafic igneous rocks have moderate acid buffering capacity. Although somewhat less reactive and slower weathering, serpentine also can be an effective buffer and field studies document that serpentine significantly increases mine water pH (Germain and others, 1994).

Soil, sediment signatures prior to mining

Soil above magmatic sulfide deposits typically has elevated metal contents, and soil geochemistry is commonly used as an exploration tool. Background and anomalous values depend on bedrock and ore compositions. The average (Levinson, 1980) copper content of soil is 20 ppm (range, 2 to 150 ppm), whereas its average nickel content is 30 ppm (range, 5 to 500 ppm); typical background and anomalous values for platinum-group elements are from 2-10 ppb and greater than 40 ppb (Smith, 1984).

Potential environmental concerns associated with mineral processing

Mining produces large amounts of waste. It is not unusual for 100 tons of rock to be extracted to obtain 1 ton of metal. Sulfide mineral-free waste may be used in road construction or similar uses. However, much waste contains sufficient sulfide minerals to generate acid and must be safely stored or isolated. Storage under water to reduce oxidation or as backfill in mining cavities is common. Surface storage requires collection of contaminated water for acid neutralization.

Tailings produced by the separation of ore from waste also contain significant amounts of sulfide minerals that can generate acid. Tailings are commonly used to backfill mined areas. Surface disposal of tailings often involves revegetation to stabilize and isolate sulfide minerals. However, these tails still have significant acid producing capability.

Smelter signatures

Magmatic sulfide ore concentrates are typically smelted and may produce SO_2 - and metal-rich emissions. These,

in turn, may cause acid rain that significantly reduces the pH of local streams and lakes and distributes metals that contaminate adjacent soil and plants. As an example, the daily discharge in 1971 from one smelter in the Sudbury, Canada, district was 32.6 tons of iron, 6 tons of nickel, 5 tons of copper, 0.13 tons of cobalt, 0.5 tons of lead, and 0.4 tons of zinc (Hutchinson, 1979). Areas that have been heavily impacted by past emissions of sulfur-rich gases from smelters include Sudbury, Canada and Noril'sk, Russia.

Whereas old smelters released virtually 100 percent of the sulfur in ore as SO₂, new smelting technologies can trap all but about 10 percent of the sulfur (Crawford, 1995). Capture of sulfur emissions can result in rapid and dramatic changes in the environment. As an example, in 1980, 45 of the 104 lakes in the Sudbury district had a pH of less than 5.5. Implementation of new SO₂-emission controls resulted in rapid changes; by 1987, 84 lakes had pH values greater than 5.5.

Climate effects on environmental signatures

The effects of various climatic regimes on the geoenvironmental signature specific to magmatic sulfide deposits is not known. However, in most cases the intensity of environmental impact associated with sulfide-bearing mineral deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell.

Geoenvironmental geophysics

Electrical geophysical techniques can be used to delineate low resistivity and polarizable minerals that may help identify the extent of sulfide deposits. In tailings and waste dumps, geophysical techniques can also be used to identify sulfide mineral concentrations and acidic water formed by sulfide mineral oxidation. Resistivity, shallow seismic refraction, and ground-penetrating radar can be used to map water-flow-controlling structures, determine thicknesses of tailing and waste dumps, and often can aid in identification of the water table. Active redox centers can be delimited by self-potential surveys, and possibly by shallow thermal probes, but their signals are susceptible to being masked by water flow and topography.

REFERENCES CITED

- Alapieti, T.T., Lahtinen, J.J., Huhma, Hannu, Hanninen, Esko, Piirainen, T.A., and Sivonen, S.J., 1989, Platinum-group element-bearing Cu-Ni sulfide mineralization in the marginal series of the early Proterozoic Suhanho-Konttjarvi layered intrusion, northern Finland, *in* Prendergast M.D., and Jones, M.J., eds., *Magmatic sulfides-the Zimbabwe volume*: London, The Institution of Mining and Metallurgy, p. 177-189.
- Blowes, D.W., and Ptacek, C.J., 1994, Acid-neutralization in inactive mine tailings, *in* Jambor, J.L., and Blowes, D.W., eds., *Short Course Handbook on Environmental Geochemistry of Sulfide Mine-wastes*, Mineralogical Association of Canada, v. 22, p. 271-292.
- Boudreau, A.E., and McCallum, I.S., 1986, Investigations of the Stillwater Complex: III. The Picket Pin Pt/Pd deposit: *Economic Geology*, v. 81, p. 1953-1975.
- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- Czamaske, G.K., Kunilov, V.E., Zientek, M.L., Cabri, L.J., Likhachev, A.P., Calk, L.C., and Oscarson, R.L., 1992, A proton-microprobe study of magmatic sulfide ores from the Noril'sk-Talnakh district, Siberia: *The Canadian Mineralogist*, v. 30, p. 249-287.
- Crawford, G.A., 1995, Environmental improvements by the mining industry in the Sudbury Basin of Canada: *Journal of geochemical exploration*, v. 52, p. 267-284.
- Eckstrand, O.R., Cogulu, E.H., and Scoates, R.F.J., 1989, Magmatic Ni-Cu-PGE mineralization in the Crustal Lake layered intrusion, Ontario, and the Fox River sill, Manitoba, *in* Morey, G.B., ed., *Workshop on the applicability of gold and platinum-group-element models in Minnesota*: Minnesota Geological Survey Information Circular 30, p. 45-46.
- Eger, P., and Lapakko, K., 1989, Use of wetlands to remove nickel and copper from mine drainage, *in* *Constructed wetlands for wastewater treatment: Municipal industrial and agricultural*, Lewis Publishers, Chelsea, Mich., p. 780-787.

- Feltis, R.D. and Litke, D.W., 1987, Appraisal of water resources of the Boulder and Stillwater Basins, including the Stillwater Complex, south-central Montana: Montana Bureau of Mines and Geology Memoir 60, 121 p.
- Germain, D., Tasse, N., and Bergeron, M., 1994, Acid mine drainage in tailings of ultramafic metasedimentary rock deposits: Case of Canadian Malartic: Geological Association of Canada, Program with abstracts, vol. 19, p. A40.
- Hammack, R.W., and Edenborn, H.M., 1992, Removal of nickel from mine waters using bacterial sulfate reduction: Applied microbiology and biotechnology, v. 37, p. 674-678.
- Hulbert, L.J., Duke, J.M., Eckstrand, O.R., Lydon, J.W., Scoates, R.F.J., Cabri, L.J., and Irvine, T.N., 1988, Geological environments of the platinum group elements: Geological Survey of Canada Open-File Report 1440, 148 p.
- Hutchinson, T.C., 1979, Copper contamination of ecosystems caused by smelter activities, *in* Nriagu, J.O., ed., Copper in the Environment, John Wiley & Sons, Inc., New York, New York, p. 451-502.
- Kwong, Y.T.J., 1993, Prediction and prevention of acid rock drainage from a geological and mineralogical perspective: MEND Project 1.32.1.
- Lapakko, K.A., and Antonson, D.A., 1994, Oxidation of sulfide minerals present in Duluth Complex rock, *in* Alpers, C.A., and Blowes, D.W., eds., Environmental geochemistry of sulfide oxidation, American Chemical Society, Washington, D.C., p. 593-607.
- Levinson, A.A., 1980, Introduction to Exploration Geochemistry: Applied Publishing Ltd., Wilmette, IL, 924 p.
- Lightfoot, P.C., and Naldrett, A.J., 1994, Proceedings of the Sudbury-Noril'sk Symposium: Ontario Ministry of Northern Development and Mines Special Volume 5, 423 p.
- Naldrett, A.J., ed., 1979, Nickel-sulfide and platinum-group element deposits: The Canadian Mineralogist, v. 17, part 2, 514 p.
- _____ 1981, Nickel sulfide deposits: Classification, composition and genesis: Economic Geology 75th Anniversary volume, p. 628-685.
- _____ 1989, Magmatic Sulfide Deposits: Oxford University Press, 186 p.
- Naldrett, A.J., Cameron, G., von Gruenewaldt, G., and Sharpe, M.R., 1987, The formation of stratiform PGE deposits in layered intrusions, Chapter 10, *in* Parsons, Ian, ed., Origins of Igneous Layering: D. Reidel Publishing Company, p. 313-397.
- Nriagu, J.O., 1979, The global copper cycle, *in* Nriagu, J.O., ed., Copper in the Environment, John Wiley & Sons, Inc., New York, New York, p. 1-17.
- _____ 1980, Global cycle and properties of nickel, *in* Nriagu, J.O., ed., Nickel in the environment, John Wiley & Sons, Inc., New York, New York, p. 1-26.
- Page, N.J., 1986a, Descriptive model of Stillwater Ni-Cu, *in* Cox, D.P. and Singer, D.A., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 11-12.
- _____ 1986b, Descriptive model of Bushveld Cr, *in* Cox, D.P. and Singer, D.A., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 13.
- _____ 1986c, Descriptive model of Duluth Cu-Ni-PGE, *in* Cox, D.P. and Singer, D.A., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 16.
- _____ 1986d, Descriptive model of Noril'sk Cu-Ni-PGE, *in* Cox, D.P. and Singer, D.A., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 17.
- _____ 1986e, Descriptive model of komatiitic Ni-Cu, *in* Cox, D.P. and Singer, D.A., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 18-19.
- _____ 1986f, Descriptive model of dunitic Ni-Cu, *in* Cox, D.P. and Singer, D.A., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 24.
- _____ 1986g, Descriptive model of synorogenic-synvolcanic Ni-Cu, *in* Cox, D.P. and Singer, D.A., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 28.
- Page, N.J., Foose, M.P., and Lipin, B.R., 1982, Characteristics of metallic deposits associated with ultramafic and mafic rocks, *in* Erickson, R.L., ed., Characteristics of mineral deposit occurrences: U.S. Geological Survey Open-File Report 82-795, p. 1-12.
- Richter, R.O. and Theis, T.L., 1980, nickel speciation in soil/water system, *in* Nriagu, J.O., ed., Nickel in the Environment, John Wiley & Sons, Inc., New York, New York, p. 189-274.
- Ritchie, I.M., 1988, Environmental management of new mining operations in developed countries: The regional copper-nickel study, *in* Salomons, W., and Forstner, U., eds., Environmental management of solid waste dredged material and mine tailings: Springer-Verlag, Berlin, p. 182-323.

- SCS Engineers, 1984, Summary of damage cases from the disposal of mining wastes: Report prepared for the U.S. Environmental Protection Agency under contract 68-02-3179, 596 p.
- Siegel, E.I., and Ericson, D.W., 1980, Hydrology and water quality of the copper-nickel study region, northeastern Minnesota: U.S. Geological Survey Water Resources Investigations Open file report 80-739, 87p.
- Smith, B.H., 1984, Geochemical exploration for nickel sulphides in lateritic terrain in Western Australia, *in* Buchanan, D.L. and Jones, M.J., eds, Sulphide deposits in mafic and ultramafic rocks, Institute of Mining and Metallurgy, London, p. 35-42.
- Snodgrass, W.J., 1980, Distribution and behavior of nickel in the aquatic environment, *in* Nriagu, J.O., ed., Nickel in the environment, John Wiley & Sons, Inc., New York, New York, p. 203-274.
- Todd, S.G., Keith, D.W., LeRoy, L.W., Shissel, D.J., Mann, E.L., and Irvine, T.N., 1982, The J-M platinum-palladium Reef of the Stillwater Complex, Montana: I. Stratigraphy and petrology: *Economic Geology*, v. 77, p. 1454-1480.
- Vermaak, C.F., 1976, The nickel pipes of Vlakkfontein and vicinity, western Transvaal: *Economic Geology*, v. 71, p. 261-286.
- Volborth, A., and Housley, R. M., 1984, A preliminary description of complex graphite, sulphide, arsenide, and platinum group element mineralization in a pegmatoid pyroxenite of the Stillwater Complex, Montana, USA: *Tschermaks Mineralogische und Petrographische Mitteilungen*, v. 33, p. 213-230.
- Zientek, M.L., Fries, T.L., and Vian, R.W., 1990, As, Bi, Hg, S, Sb, Sn, and Te geochemistry of the J-M Reef, Stillwater Complex, Montana: Constraints on the origin of PGE-enriched sulfides in layered intrusions: *Journal of Geochemical Exploration*, v. 37, p. 51-73.
- Zientek, M.L., 1993, Mineral resource appraisal for locatable minerals: the Stillwater Complex, *in* Hammarstrom, J.M., Zientek, M.L., and Elliott, J.E., eds., Mineral resource assessment of the Absaroka-Beartooth study area, Custer and Gallatin National Forests, Montana: U.S. Geological Survey Open-File Report 93-207, p. F1-F83.

SERPENTINE- AND CARBONATE-HOSTED ASBESTOS DEPOSITS (MODELS 8d, 18e; Page, 1986; Wrucke and Shride, 1986)

by Chester T. Wrucke

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

The term asbestos as used in this discussion is a collective term applied by mineralogists to certain fibrous minerals and not to other mineral species that are called asbestos in common parlance. The particular asbestos mineral that is the focus of this discussion is chrysotile.

Serpentine-hosted asbestos: Chrysotile (white asbestos) forms veins in serpentinized ultramafic rocks. Protoliths include ophiolite and stratiform complexes. The veins commonly fill fractures developed in shear zones, notably near changes in rock competency, as near contacts between serpentinite bodies and igneous masses emplaced into serpentinite. Minor asbestos veins are present in unaltered ultramafic rocks adjacent to serpentinite.

Carbonate-hosted asbestos: Veins of cross-fiber chrysotile asbestos are in tabular masses of serpentinite that replaced metalimestone during contact metamorphism related to intrusion of diabase sills, sheets, and dikes. The metalimestone developed from a cherty dolostone protolith early in the metamorphic event. Asbestos veins filled fractures incrementally during dilation caused by the diabase intrusion.

Examples

Serpentine-hosted: Canada- Thetford Mines, Black Lake, and Asbestos-Shipton areas, Quebec; Cassair, British Columbia; White Bay area, Newfoundland (Riordon, 1957; Virta and Mann, 1994). United States- Belvidere Mountain, Vt. (an extension of the Quebec deposits) (Chidester and others, 1978); Calaveras and San Benito Counties, Calif. (Rice, 1966; Virta and Mann, 1994; Coleman, in press). Africa and Europe- Bazhenovo district, central Ural Mountains, Russia (Virta and Mann, 1994); Balangero, Italy (Virta and Mann, 1994); Barberton area, South Africa (Sinclair, 1959; Anhaeusser, 1986); Troodos Complex, Cyprus (Virta and Mann, 1994); Shabani, Zimbabwe (Anhaeusser, 1986; Virta and Mann, 1994).

Carbonate-hosted: Gila County, Ariz. (Shride, 1969; 1973); Barberton-Caroline district and near Kanye, South Africa (Sinclair, 1959; Anhaeusser, 1986); Laiyuan district, Hobei Province, China (Sinclair, 1959).

Spatially and (or) genetically related deposit types

Related deposits include metadolomite-hosted talc and talc associated with serpentinized ultramafic rocks (Brown, 1973; Chidester and others, 1978); no deposit models have been developed for these deposit types.

Potential environmental considerations

- (1) Most natural exposures of asbestos-bearing rock, particularly serpentinite derived from ultramafic rocks, are readily eroded by natural agents and the activities of man because most serpentinite is composed of weak, highly fractured rock; however, some serpentinite bodies are highly resistant to erosion.
- (2) Sedimentary deposits and debris slides derived from asbestos-bearing rocks provide asbestos for redistribution by water and wind.
- (3) Vehicles driven across serpentinite and mine waste can dislodge asbestos, adding it to dust or making it readily available to surface drainage; roads also produce channels that aid run-off. The surface area of roads in the southern half of the chrysotile-bearing New Idria serpentinite in San Benito County, Calif., exceeds the area disturbed by the three largest asbestos mines in this area (Woodward-Clyde Associates, 1989).
- (4) Waste generated from asbestos mining and milling operations exposes asbestos to erosion by natural agents. The U.S. Environmental Protection Agency (EPA) considers mine waste that contains more than 1 volume percent asbestos hazardous (Derkies, 1985, p. 4-34). The California Air Resources Board considers asbestos contents of mine waste greater than 5 volume percent as a potential toxic hazard (Resolution 91-27, April 1990).
- (5) Asbestos fibers can be incorporated by surface drainage in areas of asbestos-bearing rocks and mines. In central California, water in the California Aqueduct System contains asbestos (Kanarek and others, 1980; Coleman, in press). However, the EPA has concluded that ingestion of asbestos fibers poses no significant cancer risk (U.S. Environmental Protection Agency, 1991).
- (6) Chrysotile deposits may contain small amounts of fibrous tremolite, which is classifiable by EPA as asbestos and a risk to human health (U.S. Occupational Safety and Health Administration, 1975).

(7) Health risks to humans from exposure to small quantities of chrysotile asbestos in the environment are controversial. The controversy results from the EPA assumption that any amount of asbestos is potentially hazardous.

Exploration geophysics

Remote sensing techniques can detect belts of ultramafic rocks, intrusive masses, residual iron oxide minerals, and serpentinite by infra red reflectance, thermal properties, and botanical anomalies (stress and density) in areas of serpentinite-hosted chrysotile, and can identify diabase outcrops in areas of carbonate-hosted chrysotile. Magnetic techniques can be used to identify serpentinite derived from ultramafic rocks because of their high magnetite content. However, the method may not be useful in identification of serpentinite developed from carbonate rocks. This serpentinite may contain magnetite, but the protoliths are carbonate rocks that generally have a low initial iron content, and associated serpentinite bodies are small.

References

Geology: Shride (1969, 1973), Chidester and others, (1978), Ross (1981), Anhaeusser (1986), Virta and Mann (1994). Environmental geology: Derkies (1985), Coleman (1995).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Deposit size varies from large in serpentine-hosted deposits to small in carbonate-hosted deposits. Serpentine-hosted deposits commonly contain hundreds of million tonnes of ore. In the 1950s the asbestos deposit at the Jeffrey Mine in Quebec had ore reserves as large as 450 million tonnes (Shride, 1973). By the mid 1970s, this mine, which at that time was the largest known asbestos deposit in the world, had the capacity to produce 544,000 tonnes of asbestos fiber a year (Energy, Mines, and Resources Canada, 1976). The mine was an open pit 600 m across in 1983 (Mann, 1983). The Bazhenovo district of Russia may contain larger deposits. This district had the capacity to produce at least 1.36 million tonnes of asbestos annually in the early 1980s (Mann, 1983). Reserves of chrysotile fiber at the asbestos deposit near Copperopolis, Calaveras County, Calif., are reported to be about 1.2 million tonnes (Rice, 1966). The deposit is now closed and is used as an asbestos waste dump. Production of chrysotile from the New Idria serpentinite in San Benito County, Calif. (the largest asbestos deposit in the United States) is now confined to one property, that of the King City Asbestos Corporation (KCAC, Inc.). In 1975 production from this property was 68,000 tonnes (Mumpton and Thompson, 1975). In the past, The New Idria serpentinite was the locale of many mining ventures, including chrysotile asbestos mining. All but one of these asbestos mines have ceased operations, and part of the properties are now EPA superfund sites. In 1989, the latest year for which data are available from the U.S. Bureau of Mines, the production of chrysotile from the KCAC Inc. mine and one in Orleans County, Vt. totalled 17,427 tonnes (Virta, 1989). In contrast, Arizona deposits contain a few tens to a few thousand tonnes of chrysotile asbestos (Shride, 1969). Data on chrysotile mining in Arizona (Shride, 1969 and the Yearbooks of the U.S. Bureau of Mines) for the period 1914 to 1982 (when mining ceased) indicate production of about 90,000 tonnes of asbestos fiber.

Total United States asbestos production in 1989 was 17,427 tonnes compared to world production of 4,237,659 tonnes (Virta, 1991). About 98 percent of the asbestos produced in 1990 worldwide was chrysotile (Virta and Mann, 1994).

Host rocks

Serpentine-hosted deposits: These deposits are in massive serpentinite, commonly highly sheared and widely exposed, that has largely replaced the host ultramafic protolith. Associated ultramafic rocks locally host asbestos veins.

Carbonate-hosted deposits: Serpentine in these deposits has replaced metalimestone or dolostone. In Arizona, the serpentinite bodies commonly are 1 to 3 m thick, are present at a few stratigraphic intervals in the host metalimestone section, and are structureless, except for asbestos veins.

Surrounding geologic terrane

Serpentine-hosted deposits: Most of these deposits have developed in ophiolite complexes, which are composed of oceanic crustal fragments consisting of a basal peridotite (that becomes serpentinitized) overlain in sequence by cumulate gabbro, sheeted dikes, and pillow basalt, commonly capped by deep oceanic pelagic strata. Accreted ophiolite commonly is dismembered into structurally complicated fragments. In Quebec and New England, these rocks are associated with metamorphosed sedimentary and igneous rocks, including schist, greenstone, quartzite, and

amphibolite, of early Paleozoic age. The New Idria serpentinite, Calif., which hosts the KCAC asbestos deposit and others, is completely separated from mafic oceanic crust and is surrounded by sedimentary rocks of the Cretaceous Franciscan and Panoche Formations. These rocks are folded with unconformably overlying Tertiary marine sedimentary rocks.

Carbonate-hosted deposits: Deposits of this type in Arizona are in Middle Proterozoic rocks that include siltstone, arkosic arenite, cherty dolostone, argillite, quartz arenite, local basalt, and intrusions of diabase sheets, sills, and dikes.

Wall-rock alteration

Serpentinization of host rocks and subsequent serpentinite alteration are common kinds of wall-rock alteration associated with asbestos. In serpentine-hosted deposits, serpentinite results from hydration of igneous protoliths, commonly harzburgite and dunite, which are unstable in the presence of water at crustal temperatures (Coleman, 1971; Coleman and Jove, 1993). For example, the mineralogical nature of the New Idria serpentinite probably is related to the relative amounts of orthopyroxene and olivine in the primary peridotite. Reactions with water can be written:

- 1) $3\text{Mg}_2\text{Si}_2\text{O}_6$ (pyroxene) + $4\text{H}_2\text{O}$ = $2\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$ (serpentine) + 2SiO_2 (quartz)
- 2) $2\text{Mg}_2\text{SiO}_4$ (olivine) + $3\text{H}_2\text{O}$ = $\text{Mg}_3\text{Si}_2\text{O}_5(\text{OH})_4$ (serpentine) + $\text{Mg}(\text{OH})_2$ (brucite)

Reaction 1 produces weathering-resistant silica-bearing serpentinite that forms pinnacles, common in the New Idria serpentinite, whereas reaction 2 produces predominantly highly weathered and rounded boulders and fine soil-like material (Malcolm Ross, written commun., 1995). Serpentinization releases calcium that becomes available for secondary minerals. Iron in the primary silicate minerals, when not incorporated into serpentinite, may form magnetite. With increasing metamorphic temperature, lizardite of the original serpentinite is replaced by antigorite, which at higher temperatures is converted, by dehydration, to talc, olivine, and water (Coleman and Jove, 1993). Common alteration products in metamorphosed serpentinites of Quebec and Vermont are talc in steatite and schistose masses, talc-carbonate rocks, and quartz-carbonate bodies (Chidester and others, 1978).

Late stage serpentinization of carbonate-hosted deposits follows dedolomitization and development of calcium-magnesium silicate minerals during contact metamorphism. Subsequent serpentine alteration proceeds as outlined for serpentinite-hosted deposits.

Nature of ore

Serpentine-hosted deposits: These deposits commonly consist of stockworks (networks of veins) of cross-fiber veins that are aggregates of two or more thin parallel layers of fibers oriented about normal to vein walls. Most deposits contain some slip-fiber veins composed of fibers in the plane of the fracture. In a few deposits, this is the principal fiber type. In the New Idria serpentinite, ore is in sheared and pulverized serpentinite and consists of flake-like agglomerates and sheet-like masses of finely matted chrysotile (Mumpton and Thompson, 1975). Much of this ore may be secondary (see section below entitled "Secondary mineralogy"). Asbestos contents vary widely in the serpentine-hosted deposit type. Typical deposits contain 5 to 15 volume percent asbestos fiber; in the New Idria serpentinite, ore contains in excess of 50 volume percent chrysotile (Mumpton and Thompson, 1975).

Carbonate-hosted deposits: Ore zones consist of sets of cross-fiber veins subparallel to bedding in the serpentinized host. Commonly, veins are composed of multiple parallel layers in which the fibers are oriented about at right angles to vein walls and aggregate 1 to 20 cm in width; multiple layers indicate incremental development. Veins pinch and swell, anastomose, and vary in dip. Productive zones may be 10 cm to a few decimeters thick and constitute as much as 40 volume percent of a serpentinite body (Shride, 1969; Otton and others, 1981). However, asbestos veins commonly are contained in much greater thicknesses of massive, barren serpentinite. Chrysotile veins locally are in fine-grained calc-silicate rocks developed from cherty dolomite.

Deposit trace element geochemistry

Manganese, chromium (trivalent), copper, nickel, and platinum are rare elements found in chrysotile (Ross, 1981; Wicks and O'Hanley, 1988). Hexavalent chromium, known to be toxic, is not present in these asbestos deposits. Trace element composition has not been considered an environmentally significant aspect of chrysotile deposits.

Ore and gangue mineralogy and zonation

In serpentine- and carbonate-hosted deposits, the only ore mineral is chrysotile. Serpentinite-hosted deposits contain magnetite in the serpentine gangue and locally talc, as well as quartz-calcite veins (Riordon, 1957). In Canadian deposits, magnetite commonly is concentrated in wall rock adjacent to asbestos veins, along vein walls, in partings between layers of multiple veins, and can be disseminated parallel to chrysotile fibers (Riordon, 1957). Chrysotile, brucite, and magnetite are common in serpentine of the New Idria body (Coleman, in press). Carbonate-hosted deposits may include sparse calcite veins, otherwise the gangue is serpentine.

Mineral characteristics

Chrysotile is one of six mineral species called asbestos because of their fibrous habit (Skinner and others, 1988). Of these, chrysotile is the only fibrous serpentine mineral. The other five asbestos minerals belong to the amphibole group; these are grunerite asbestos (commonly referred to as amosite), riebeckite asbestos (commonly referred to as crocidolite), anthophyllite asbestos, tremolite asbestos, and actinolite asbestos. Chrysotile ($Mg_3Si_2O_5(OH)_4$) consists of layers of linked SiO_4 tetrahedra and misfit layers of linked $MgO_2(OH)_4$ tetrahedra that together roll into sheets, making hollow tubes having diameters of about 25 nm (Ross, 1981). Most chrysotile contains less than 2 weight percent iron as FeO, though as much as 8 percent has been reported (Wicks and O'Hanley, 1988). Small amounts of aluminum, manganese, magnesium, calcium, potassium, and sodium also may be present (Ross and others, 1984). Vein fibers range in length from less than 5 μm to 10 cm or more. They can vary in flexibility, hardness, tensile strength, and other physical properties and chemical properties of importance in determining their commercial use (Shride, 1973).

Secondary mineralogy

Although serpentine minerals are considered to be stable in the upper crust (Coleman and Jove, 1993), studies in California show that they are unstable in the range of pH and Mg^{2+} and $Si(OH)_4$ concentrations encountered in most soil (Mumpton and Thompson, 1966; Wildman and others, 1971). Iron-rich montmorillonite is a common product of serpentine in this soil type (Wildman and others, 1971). Brucite ($Mg(OH)_2$), one of the hydrothermal minerals that develops during serpentinization and makes up 7 to 8 volume percent of the New Idria serpentinite, is destroyed in the weathering zone, producing coalingite (an iron- and magnesium-bearing carbonate), compositionally similar pyroaurite (Mumpton and Thompson, 1966), hydromagnesite, and secondary chrysotile (Mumpton and Thompson, 1975). Some chrysotile is developed during tectonic milling and may be the most important process in the formation of chrysotile at the New Idria deposit (R.G. Coleman, written commun., 1995). Deeply weathered serpentinite can produce the nickel-bearing minerals nepouite and pecoraite (Mumpton and Thompson, 1975), but most serpentine contains only very small amounts of nickel.

Tremolite, an amphibole, can be fibrous and is associated with chrysotile deposits, particularly at Thetford Mines, Quebec; Troodos, Cyprus; and Balangero, Italy (R.G. Coleman, written commun., 1995). The EPA classifies tremolite as asbestos if the particles have an aspect ratio of 3:1. The amount and distribution of tremolite asbestos in chrysotile deposits is poorly known. It is extremely scarce in the New Idria, Calif., deposits (Coleman, in press), and it makes up less than one volume percent of the dust in Quebec mines and mills (Mossman and others, 1990).

Topography, physiography

Serpentine-hosted deposits: These deposits are easily eroded. Serpentinite bodies commonly are well exposed and therefore are readily eroded. The asbestos deposit at Belvidere Mountain, Vt., is on a hillside in an area having relief of 200 m in a radius of 1.6 km (Chidester and others, 1951). The New Idria serpentinite body in San Benito County, Calif., occupies a high ridge, as illustrated in Mumpton and Thompson (1975), that includes rock exposures barren of vegetation. Evidence of contact dislocation shows that this serpentinite body is rising tectonically, exposing this soft material to long term erosion (Coleman, in press).

Carbonate-hosted deposits: Chrysotile-bearing serpentinite zones in Arizona are soft and weakly resistant to weathering. However, these zones commonly are exposed in cliffs and steep slopes, protected by the more resistant, overlying metalimestone beds, which reduces exposure of serpentinite and chrysotile to erosion.

Hydrology

Streams draining asbestos-bearing serpentinite can pick up chrysotile fibers. Most streams draining the Belvidere Mountain deposit, Vt. lead to the Gihon and Lamoille Rivers and Lake Champlain, but some reach Quebec via the Missisquoi River. Stream drainages from the northeast and southeast parts of the New Idria serpentinite, Calif., lead

to the San Joaquin Valley. This area drains to the west via the San Benito River to the Pacific Ocean. Debris slides along the flanks of the serpentinite body and in the main drainage channels contain huge amounts of asbestos-bearing material available for removal and dispersion by streams (Cowan, 1979). During flood stage, streams flowing into the San Joaquin Valley from the New Idria mass have introduced sediment into the California aqueduct (Coleman, in press). Asbestos fibers also have been found in the water supply for San Francisco (Kanarek and others, 1980). Drainage from carbonate-type chrysotile deposits in Arizona reaches the watershed of the Salt River, which flows to Phoenix via several reservoirs.

Mining and milling methods

Serpentine-hosted deposits: Exploitation of these deposits is mostly by open-pit mining. Block caving and other underground methods have been used. Milling generally is a dry process and follows practices used, slightly modified, since the early days of this century (Mann, 1983). Ore is crushed, screened, and dried. Drying is accomplished using hot air, which is filtered after the fibers are dried. Processing and packaging methods have improved significantly in recent years, which makes it possible to handle asbestos in a nearly dust-free environment. Most producers grade and classify milled asbestos fibers as a function of fiber length, using a standard developed in Canada (Energy, Mines, and Resources Canada, 1976; Mann, 1983). A wet process for milling chrysotile was installed in 1990 at the Baie Verte Mines in Newfoundland (Stewart and others, 1990). In this process, mill feed is wet screened, classified, then dried in a propane-fired dryer. Impurities are collected in a thickener and pumped to tailings dumps. A wet process was used in 1991 at the KCAC Inc. mine in San Benito County, Calif, (Virta, 1991).

Carbonate-hosted deposits: Chrysotile mining in Arizona has been by small-scale underground methods using adits, room and pillar methods, and stoping with backfill. Milling of chrysotile ore in Arizona was stopped by court order in 1974. The milling process consisted of crushing the ore, beating it to free the fibers, then removing the fibers by screening and air separation (Bowles, 1955). Waste rock and unwanted fibers were consigned to tailings dumps.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Stream channels that drain chrysotile-bearing serpentinite contain asbestos as a natural erosion product. Where serpentinite masses crop out in mountainous terrane, as in San Benito County, Calif., chrysotile-bearing debris in landslides, debris flows, and bedrock exposures provide extensive sources of asbestos materials to local streams. Some of these fibers have reached the California aqueduct on the west side of the San Joaquin Valley.

Asbestos mobility from solid mine wastes

Mine dumps and mill tailings at chrysotile deposits are sources of asbestos fibers for surface water and are more easily eroded than outcrops.

Soil, sediment signatures prior to mining

Soil developed on asbestos-bearing bedrock may contain asbestos fibers. The soil over the New Idria body is composed of chrysotile and brucite with some lizardite and (or) antigorite, plus minor amounts of other minerals.

Potential environmental concerns associated with mineral processing

The principal concerns include dust and tailings from asbestos milling operations. Asbestos fibers in tailings are available for airborne and fluvial transport.

Smelter signatures

Not applicable to asbestos.

Climate effects on environmental signatures

Where serpentinitization is ongoing, meteoric water becomes saturated with calcium hydroxide and can precipitate brucite, portlandite, and carbonate minerals. In arid climates, weathering can lead to the precipitation of brucite, carbonate minerals, chrysotile, and talc (Coleman and Jove, 1993). In humid conditions, serpentinite can be dissolved leaving a residue rich in iron and smectite.

Chrysotile in some environments is known to survive for thousands to millions of years after being subjected to erosion and transport to distant sites. For example, accumulations of chrysotile fibers eroded from the New Idria,

Calif., serpentinite have been identified in downstream sedimentary accumulations such as terrace deposits and alluvial fans (Coleman, in press). Chrysotile also is preserved in the Big Blue Formation of Miocene age, which contains abundant debris eroded from the New Idria serpentinite (Carlson, 1981).

Geoenvironmental geophysics

See exploration geophysics.

CONTROVERSY REGARDING HEALTH RISKS TO HUMANS FROM CHRYSOTILE ASBESTOS

The risk of asbestos to human health has been known at least since 1906 when workers in an asbestos weaving mill in France died (D'Agostino and Wilson, 1993). In the 1920s, a death from asbestosis (fibrosis of the lung) was reported and the disease was named (Sawyer, 1987). However, not until the 1960s were the biologic effects of asbestos fibers documented in great detail and a relationship clearly established between exposure to asbestos and lung disease, including cancer. As a result of concern developed from increasing knowledge of health hazards associated with asbestos minerals, the Occupational Safety and Health Administration (OSHA) in 1971 issued regulations restricting airborne asbestos in the workplace, and in 1987 OSHA established the current workplace standard of 0.2 fibers per cubic centimeter of air. However, the regulations do not discriminate between fibers of the different asbestos minerals. Since the establishment of these regulations, numerous studies have demonstrated that various asbestos minerals have significantly different associated health effects. For example, the few cases of mesothelioma (cancer of the pleura or peritoneum) in Canadian chrysotile miners and mill workers appear to be not from chrysotile but perhaps from small amounts of tremolite asbestos, and a study of British workers engaged in the manufacture of friction materials using only chrysotile showed no excess of deaths from lung diseases (Mossman and others, 1990). Health effects related to occupational exposure to chrysotile are the least of any asbestos mineral; people exposed to chrysotile alone, at abundances more than 10 times higher than recommended by the EPA, experience no excess lung cancer (Coleman, in press).

RISK ASSESSMENT

Hazards resulting from inhalation of asbestos fibers have been documented by the EPA and have been the topic of considerable scientific inquiry (Ross, 1981, 1984; Skinner and others, 1988; Mossman and others, 1990; D'Agostino and Wilson, 1993; Ross and Skinner, 1994; McDonald and McDonald, 1995). Although the relationship between asbestos and lung diseases is well documented, debate continues regarding the risk from low level exposure to asbestos fiber. In a report prepared for the California Environmental Protection Agency, risk related to asbestos was not ranked because data on low level exposure were considered inadequate (California Comparative Risk Project, 1994). Studies show that important factors to be considered in evaluating risk associated with asbestos inhalation include type of asbestos mineral, length and diameter of the asbestos fibrils, amount of asbestos inhaled, and the duration of the exposure. Yet, despite conclusions that risks from chrysotile asbestos are almost certainly lower than for other asbestos minerals (D'Agostino and Wilson, 1993), uncertainty in the degree of risk from exposure to chrysotile remains. The uncertainty results in part from disagreement concerning whether an exposure threshold exists and, if so, at what fiber concentration below which inhalation is safe (D'Agostino and Wilson, 1993).

The EPA has concluded that inhalation of any amount of asbestos is potentially hazardous, that a single asbestos fiber can be lethal (Abelson, 1990). This conclusion results from belief that a linear relationship exists between asbestos dose and health risk such that risk exists even at very low levels of exposure (D'Agostino and Wilson, 1993). According to this theory, any exposure to asbestos poses a risk. In a nonlinear relation, risk from exposure decreases rapidly at low levels and a threshold value can be reached below which the risk is zero. Recent studies suggest that low-level exposure to chrysotile asbestos in the environment has generated unwarranted concern based on speculation (D'Agostino and Wilson, 1993) and that the single-fiber view is unproved (Abelson, 1990). Other studies suggest that a "threshold" value, below which exposure to chrysotile asbestos causes no measurable health effects, can be identified (Ross, 1987).

Estimates of risk to human health from numerous activities, including everyday risks, have been quantified, and a few attempts have been made to quantify risk of exposure to chrysotile asbestos under different environmental conditions (D'Agostino and Wilson, 1993; Coleman, in press). For example, data show that risks from inhaling asbestos during recreational activities at the chrysotile-bearing New Idria, Calif., serpentinite or from exposure to asbestos in schools are low. Coleman (1995) concluded that "the apparent risk in making one trip by automobile to New Idria is 300 times greater than inhaling [chrysotile] fibers during a lifetime of recreation in this area." Risks from occupying schools containing chrysotile fibers are even lower and have been categorized as harmlessly small

(Abelson, 1990; Wilson and others, 1994).

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REFERENCES CITED

- Ableson, P.H., 1990, The asbestos removal fiasco: *Science*, v. 247, p. 1017.
- Anhaeusser, C.R., 1986, The geological setting of chrysotile asbestos occurrences in southern Africa, *in* Anhaeusser, C.R., and Maske, S., eds., *Mineral deposits of southern Africa*: Johannesburg, Geological Society of South Africa, p. 359-375.
- Bowles, Oliver, 1955, The asbestos industry: U.S. Bureau of Mines Bulletin 552, 122 p.
- Brown, C.E., 1973, Talc, *in* Brobst, D.A., and Pratt, W.P., eds., *United States mineral resources*: U.S. Geological Survey Professional Paper 820, p. 619-626.
- California Comparative Risk Project, 1994, *Toward the 21st century: planning for protection of California's environment*: California Environmental Protection Agency, 642 p.
- Carlson, Christine, 1981, *Sedimentary serpentinites of the Wilbur Springs area-a possible Early Cretaceous structural and stratigraphic link between the Franciscan complex and the Great Valley sequence*: Stanford, Stanford University, M.S. thesis, 105 p.
- Chidester, A.H., Albee, A.L., and Cady, W.M., 1978, Petrology, structure, and genesis of the asbestos-bearing ultramafic rocks of the Belvidere Mountain area in Vermont: U.S. Geological Professional Paper 1016, 95 p.
- Chidester, A.H., Billings, M.P., and Cady, W.M., 1951, Talc investigations in Vermont, Preliminary report: U.S. Geological Survey Circular, 33 p.
- Coleman, R.G., 1971, Petrologic and geophysical nature of serpentinites: *Geological Society of America*, v. 82, p. 897-917.
- _____ (in press), *New Idria serpentinite, a land management dilemma*: *Engineering and Environmental Geology*.
- Coleman, R.G., and Jove, C., 1993, Geological origins of serpentinites, *in* *The vegetation of ultramafic (serpentine) soils*, Proceedings of the First International Conference on serpentine ecology: Andover, Intercept Ltd., p. 1-17.
- Cowan, D.S., 1979, Serpentine flows on Joaquin Ridge, southern Coast Ranges, California: *Geological Society of America Bulletin*, v. 81, p. 2615-2628.
- D'Agostino, Ralph, Jr., and Wilson, Richard, 1993, Asbestos: The hazard, the risk, and public policy, *in* Foster, K.R., Bernstein, D.E., and Huber, P.W., eds., *Phantom risk*: Cambridge, MIT, p.183-210.
- Derkies, Dan, 1985, *Wastes from the extraction and beneficiation of metallic ores, phosphate rock, asbestos, overburden from uranium mining, and oil shale, prepared for Environmental Protection Agency*: National Technical Information Service Report PB 88-162631.
- Energy, Mines, and Resources Canada, 1976, *Asbestos: Energy, Mines and Resources Canada Mineral Bulletin MR 155*, 26 p.
- Kanarek, M.S., Conforti, P.M., Jackson, L.A., Cooper, R.C., and Murcho, J.C., 1980, Asbestos in drinking water and cancer incidence in the San Francisco Bay area: *American Journal of Epidemiology*, v. 112, p. 54-72.
- Mann, E.L., 1983, Asbestos, *in* Lefond, S.J., ed., *Industrial minerals and rocks*: New York, American Institute of Mining, Metallurgical, and Petroleum Engineers, p. 435-484.
- McDonald, J.C., and McDonald, A.D., 1995, Chrysotile, tremolite, and mesothelioma: *Science*, v. 267, p. 778-779.
- Mossman, B.T., Bignon, J., Corn, M., Seaton, A., and Gee, J.B.L., 1990, Asbestos: scientific developments and implications for public policy: *Science*, v. 247, p. 294-301.
- Mumpton, F.A., and Thompson, C.S., 1966, The stability of brucite in the weathering zone of the New Idria serpentinite: *Clays and Clay Minerals*, v. 14, p. 249-257.
- _____ 1975, *Mineralogy and origin of the Coalinga asbestos deposit*: *Clays and Clay Minerals*, v. 23, p. 131-143.
- Otton, J.K., Light, T.D., Shride, A.F., Bergquist, J.R., Wrucke, C.T., Theobald, P.K., Duval, J.S., and Wilson, D.M., 1981, *Mineral resources of the Sierra Ancha Wilderness and Salome Study Area, Gila County, Arizona*: U.S. Geological Survey Miscellaneous Field Studies Map MF-1162-H, scale 1:48,000.
- Page, N.J., 1986, Descriptive model of serpentine-hosted asbestos, *in* Cox, D.P. and Singer, D.A., *Mineral deposit models*: U.S. Geological Survey Bulletin 1693, p. 46.
- Rice, S.J., 1966, Asbestos, *in* *Mineral resources of California*: California Division of Mines and Geology Bulletin 191, p. 86-92.

- Riordon, P.H., 1957, Asbestos, *in* The geology of Canadian industrial mineral deposits: Sixth Commonwealth Mining and Metallurgical Congress, p. 3-53.
- Ross, Malcolm, 1981, The geologic occurrences and health hazards of amphibole and serpentine asbestos, *in* Veblen, D.R., ed., Amphiboles and other hydrous pyriboles-mineralogy: Mineralogical Society of America Reviews in Mineralogy, v. 9A, p. 279-323.
- _____, 1984, A survey of asbestos-related disease in trades and mining occupations and in factory and mining communities as a means of predicting health risks of nonoccupational exposure to fibrous minerals: American Society for Testing and Materials Special Publication 834, p. 51-104.
- _____, 1987, Minerals and health: the asbestos problem, *in* Pierce, W.H., ed., Aggregates to zeolites (AZ) in Arizona and the Southwest, Proceedings of the 21st Forum on the Geology of Industrial Minerals, April 9-12, 1985: Tucson, Arizona Bureau of Geology and Mineral Technology, p. 101-115.
- Ross, Malcolm, Kuntze, R.A., and Clifton, R.A., 1984, A definition of asbestos: American Society of Testing and Materials Special Technical Publication 834, p. 139-147.
- Ross, Malcolm, and Skinner, C.W., 1994, Minerals and cancer: *Geotimes*, v. 39, p. 13-15.
- Sawyer, R.N., 1987, Asbestos exposure: health effects update: *National Asbestos Council Journal*, v. 5, no. 2, p. 25-29.
- Shride, A.F., 1969, Asbestos, *in* Mineral and water resources of Arizona: Arizona Bureau of Mines Bulletin 180, 303-311.
- _____, 1973, Asbestos, *in* Brobst, D.A., and Pratt, W.P., eds., United States mineral resources: U.S. Geological Survey Professional Paper 820, p. 63-73.
- Sinclair, W.E., 1959, Asbestos, its origin, production, and utilization: London, Mining Publications, 559 p.
- Skinner, H.C.W., Ross, Malcolm, and Frondel, Clifford, 1988, Asbestos and other fibrous materials, mineralogy, crystal chemistry, and health effects: New York, Oxford, 204 p.
- Stewart, P., French, G., and Anthony, D., 1990, Baie Verte wet process: *Industrial Minerals*, no. 273, p. 51-53.
- U.S. Environmental Protection Agency, 1991, Final national primary drinking water rules: 56 *Federal Register* 3578 (Jan. 30, 1991).
- U.S. Occupational Safety and Health Administration, 1975, Occupational exposure to asbestos: *Federal Register*, Oct. 9, 1975, p. 47652-47660.
- Virta, R.L., 1989, Asbestos, *in* Metals and minerals: U.S. Bureau of Mines Minerals Yearbook, v. 2, p. 127-134.
- _____, 1991, Asbestos, *in* Metals and minerals: U.S. Bureau of Mines Minerals Yearbook, v. 1, p. 245-252.
- Virta, R.L., and Mann, E.L., 1994, Asbestos, *in* Carr, D.D., ed., *Industrial minerals and rocks*, 6th edition: Littleton, Society for Mining, Metallurgy, and Exploration, Inc., p. 97-124.
- Wicks, F.J., and O'Hanley, D.S., 1988, Serpentine minerals: structures and petrology, *in* Bailey, S.W., ed., *Hydrous phyllosilicates*: Mineralogical Society of America Reviews in Mineralogy, v. 19, p. 91-167.
- Wildman, W.E., Whittig, L.D., and Jackson, M.L., 1971, Serpentine stability in relation to formation of iron-rich montmorillonite in some California soils: *American Mineralogist*, v. 56, p. 587-602.
- Wilson, Richard, Langer, A.M., Nolan, R.P., Bernard, J., Gee, L., and Ross, Malcolm, 1994, Asbestos in New York City public school buildings--public policy: is there a scientific basis?: *Regulatory Toxicology and Pharmacology*, v. 30, p. 161-169.
- Woodward-Clyde Associates, 1989, Draft regional study of mining disturbances and exploration-related disturbances of asbestos-bearing material in the New Idria-Coalinga-Table Mountain study region: U.S. Environmental Protection Agency Report prepared under EPA contract no. 68-01-6939.
- Wrucke, C.T., and Shride, A.F., 1986, Descriptive model of carbonate-hosted asbestos, *in* Cox, D.P. and Singer, D.A., *Mineral deposit models*: U.S. Geological Survey Bulletin 1693, p. 98.

CARBONATITE DEPOSITS (MODEL 10; Singer, 1986a)

by Peter J. Modreski, Theodore J. Armbrustmacher, and Donald B. Hoover

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Carbonatites are intrusive carbonate-mineral-rich igneous rocks, many of which contain distinctive abundances of apatite, magnetite, barite, and fluorite, that may contain economic or anomalous concentrations of rare earth elements, phosphorus, niobium, uranium, thorium, copper, iron, titanium, barium, fluorine, zirconium, and other rare or incompatible elements. They may also be sources of mica or vermiculite. Carbonatites may form central plugs within zoned alkalic intrusive complexes, or as dikes, sills, breccias, and veins.

Examples

Oka, Quebec; Iron Hill and Gem Park, Colo.; Magnet Cove, Ark.; St. Honore, Quebec; Mountain Pass, Calif.; Phalaborwa, South Africa; Jacupiranga, Brazil; Kovdor, Russia.

Spatially and (or) genetically related deposit types

Vein deposits of thorium, fluorite, or rare earth elements may be associated with carbonatites.

Potential environmental considerations

Most carbonatite deposits are likely to be mined on a large scale in open pit mines. Potential impacts include radioactivity from uranium and (or) thorium in waste rock or sediment; dust from mining activities; acid- and (or) metal-contaminated drainage from pyrite-rich carbonatites; and possible water contamination from spillage or leakage of chemical solutions used to leach and process ore. Asbestiform amphiboles, such as riebeckite, that are present in waste dumps associated with some carbonatite deposits may pose another health risk.

Exploration geophysics

The geophysical signature of carbonatite complexes is variable (Hoover, 1992). In many complexes, concentrations of magnetic minerals produce positive magnetic anomalies. Similarly, concentrations of radioactive minerals cause pronounced radiometric anomalies associated with many carbonatite complexes.

References

Heinrich (1966), Erdosh (1979), Bell (1989), Notholt and others (1989).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Minable carbonatite deposits typically range in size from approximately 6 to 300 M metric tons (Singer, 1986b).

Host rocks

Rocks constituting carbonatite deposits may include varieties of carbonatite, including calcite-rich (sövite), dolomite-rich (rauhaugite), iron-rich carbonatite, silico-carbonatite, etc. Carbonatite is typically associated with concentrically zoned complexes of alkaline-igneous rocks, though some deposits may consist of dikes or thick sheets. Associated igneous rocks typically include ijolite, melteigite, pyroxenite, and nepheline syenite. Carbonatites are typically associated with undersaturated igneous rocks that are miaskitic (nearly peralkaline) rather than agpaitic (peralkaline). Any rock type, often including granite and other intrusive rocks, gneiss and other metamorphic rocks, may host the alkaline-igneous complexes. Host rocks are often fenitized (alkali metasomatized) by alkali-rich fluids evolved from carbonatite complexes.

Surrounding geologic terrane

Carbonatite and carbonatite-alkaline igneous complexes are typically located in relatively stable, intra-plate regions, often within Precambrian shield or continental platform areas. Some may develop near plate margins or be associated with rifted or incipiently rifted continental plates. Some are associated with alkaline volcanic activity. Carbonatites range in age from Archean to Recent.

Wall-rock alteration

Carbonatite-containing complexes are typically surrounded by an aureole of metasomatized rock that is characteristically moderately to intensely fenitized. Quartzo-feldspathic wall rocks are typically converted to quartz-free rocks composed of alkali feldspar, aegirine and other sodic pyroxenes, and subordinate alkali amphibole. Other types of hydrothermal alteration, such as chloritization of ferromagnesian minerals, may also be present.

Nature of ore

Ore minerals may be disseminated throughout a large volume of carbonatite, or may be banded and concentrated in certain intrusive, alteration, or breccia zones, or in carbonatite dikes and sills.

Deposit trace element geochemistry

Most deposits are enriched in Th, U, Ti, Zn, Nb, Y, Mo, Cu, V, P, Mn, S, La, Ce, Sm, Eu, Pb, Zr, and Ba.

Ore and gangue mineralogy and zonation

Ore minerals may be disseminated throughout carbonatites, or concentrated in bands or zones. Multiple stages of igneous activity and metasomatic replacement may have produced localized ore mineral concentrations. Carbonatite complexes may include multiple stages of carbonatite dikes and veins, which cut earlier carbonatite and host rocks, crosscut each other, and grade into low-temperature veins containing carbonate minerals, fluorite, and quartz.

Mineral characteristics

Elemental and mineral associations include: phosphate-iron (fluorapatite, carbonate-fluorapatite, magnetite); niobium (pyrochlore, perovskite, niocalite); rare earth element-barium (bastnaesite, monazite, parisite, barite). Other common major and accessory minerals include calcite, dolomite, ankerite, ilmenite, strontianite, fluorite, pyrrhotite, pyrite, molybdenite, galena, chalcopyrite, sphalerite, biotite, phlogopite, pyroxenes, amphiboles, forsterite, hematite, zircon, anatase, brookite, and rutile.

Secondary mineralogy

Dissolution of carbonate and residual concentration of iron oxide are the dominant secondary processes. Partial dissolution and reprecipitation of apatite may result in near-surface enriched deposits of francolite (carbonate-apatite).

Topography, physiography

Variable. Topography is often controlled by the more resistant silicate rocks associated with carbonatite. Carbonatite plugs have a tendency to form subdued topography due to dissolution of carbonate minerals by ground and meteoric water. Dikes may stand out as resistant features in arid climates, but may be removed by dissolution in wet climates. Karst processes may produce topographic lows filled by lake sediment and underlain by residual concentrations of insoluble minerals from carbonatite.

Hydrology

Most carbonatite deposits are within concentrically zoned igneous complexes. Most rock in this type of setting is relatively solid, unfractured, and not associated with major fault or shear zones. Consequently, features that focus water flow are scarce in association with carbonatite complexes. Some parts of deposits may, however, contain vuggy or breccia zones with increased permeability. Dissolution by ground water does create the potential for genesis of permeable channels in particularly calcite-rich carbonatites.

Mining and milling methods

Most carbonatite deposits are mined by large scale, open-pit methods. Separation of ore from waste depends on the commodity being sought. Physical concentration by density and flotation is commonly employed. Rare earth element recovery requires leaching by acid or alkaline solutions, and specific rare earth element concentrates are typically purified using solvent extraction.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Stream sediments downstream from carbonatite deposits commonly contain anomalous abundances of thorium, barium, niobium, and rare earth elements, including lanthanum, cerium, neodymium, and samarium (U.S. Geological

Survey, 1991; Haxel, in press).

Metal mobility from solid mine wastes

Rare earth elements, uranium, thorium, and niobium are likely to be present in relatively stable, insoluble mineral forms that decompose slowly. Production of metal-charged acid drainage may be appreciable from pyrite- or sulfide-rich carbonatite. However, carbonate-rich host rocks buffer acid drainage in most cases.

Soil, sediment signatures prior to mining

Soil and weathered rock associated with carbonatite deposits are likely to be enriched in iron, phosphorous, niobium, and rare earth elements and potentially thorium, uranium, titanium, barium, zirconium, and other elements as well.

Potential environmental concerns associated with mineral processing

Tailings or waste are likely to contain above-normal amounts of uranium and (or) thorium. Weathering of waste from pyrite-rich carbonatites has the potential to produce acid drainage but abundant carbonate minerals generally consume acid so generated. Chemical processing used to extract phosphate has the potential to produce acid drainage if liquids or solids escape treatment cycles.

Smelter signatures

Little data available. Most mineral commodities recovered from carbonatites are those separated by mechanical separation means or chemical solution; neither smelting nor associated emissions are relevant factors.

Climate effects on environmental signatures

The effects of various climatic regimes on the geoenvironmental signature specific to carbonatite deposits are not known. Because these deposits have relatively low sulfide mineral contents and because carbonate minerals that have abundant acid consumption potential are abundant in association with these deposits, environmental signatures associated with carbonatite deposits probably are not much affected by climatic regime variation.

Geoenvironmental geophysics

Where radon hazards may be of concern, gamma-ray spectrometry can easily distinguish between the three natural radioelements, potassium, thorium, and uranium, and provide quantitative estimates of their concentrations. Where sulfide minerals are present, in mineralized rock or mine waste, induced polarization methods can detect their presence. Enhanced vegetation development, typically associated with complexes in which phosphorous and potassium abundances have been enriched, can be detected by remote sensing.

REFERENCES CITED

- Bell, Keith, ed., 1989, Carbonatites, genesis and evolution: London, Unwin Hyman, 618 p.
- Erdosh, G., 1979, The Ontario carbonatite province and its phosphate potential: *Economic Geology*, v. 74, no. 2, p. 331-338.
- Haxel, G.B., in press, Ultrapotassic rocks, carbonatite, and rare earth element deposit, Mountain Pass, California, in Theodore, T.G., ed., Evaluation of metallic mineral resources and their geologic controls in the East Mojave National Scenic Area, San Bernadino County, California: U.S. Geological Survey Bulletin.
- Heinrich, E.W., 1966, The geology of carbonatites: Chicago, Rand McNally, 555 p.
- Hoover, D.B., 1992, Geophysical model of carbonatites, in Hoover, D.B., Heran, W.D., and Hill, P.L., eds., The Geophysical Expression of Selected Mineral Deposit Models: U.S. Geological Survey Open-File Report 92-557, p. 80-84.
- Notholt, A.J.G., Sheldon, R.P., and Davidson, D.F., 1989, Phosphate deposits of the world, v. 2, phosphate rock resources: Cambridge, Cambridge University Press, 566 p.
- Singer, D.A., 1986a, Descriptive model of carbonatite deposits, in Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 51.
- _____, 1986b, Grade and tonnage model of carbonatite deposits, in Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 52-53.
- U.S. Geological Survey, 1991, Evaluation of metallic mineral resources and their geologic controls in the East Mojave National Scenic Area, San Bernadino County, California: U.S. Geological Survey Open-File Report 91-427, 278 p.

TH-RARE EARTH ELEMENT VEIN DEPOSITS (MODEL 11d; Staatz, 1992)

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SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Deposits consist of thorium and rare earth element minerals in a gangue consisting of smoky quartz, potassic feldspar, iron oxide minerals, fluorite, and barite, in thorium- and rare earth element-bearing veins and carbonatite dikes. Archean to Recent alkaline intrusive rocks and intrusive carbonatite stocks are frequently spatially and perhaps genetically related to the deposits. At some localities, alkaline rocks and carbonatites have not yet been identified. Veins are less than 1 m to 1,350 m long and less than 1 cm to more than 15 m wide and are localized along fracture zones of varying prominence. Carbonatite dikes are less than 1 m to 100 m long and 1 cm to 6 m wide. Narrow fenitized (alkali metasomatized) wall-rock selvages are adjacent to veins and dikes. Thorium veins have relatively high thorium-rare earth element ratios; carbonatite dikes have relatively high rare earth element-thorium ratios and may also contain significant concentrations of niobium.

Examples

Thorium veins: Wet Mountains area and Powderhorn district, Colo.; Capitan Mountain and Laughlin Peak, N. Mex.; Lemhi Pass district, Idaho; and Bokan Mountain district, Alaska. Carbonatite dikes: Wet Mountains area (especially Gem Park) and Powderhorn district (especially near Iron Hill), Colo.; Mineral Hill district, Idaho-Mont.; Rocky Boy's Indian Reservation, Bearpaw Mountains, Mont.; Bear Lodge Mountains, Wyo.; Mountain Pass, Calif.; and Magnet Cove and Potash Sulphur Springs, Ark.

Spatially and (or) genetically related deposit types

Deposits of niobium, titanium, iron, vermiculite, manganese oxide, uranium, and fluorite are present within and immediately adjacent to thorium and rare earth element veins and carbonatite dikes.

Potential environmental considerations

Because of their elongate nature, both thorium-rare earth element veins and carbonatite dikes could be developed by underground mining techniques. Ore and waste dump rock are highly radioactive because of their thorium content; fenitized host rock is similarly radioactive. Thorium-rare earth element veins have moderately high sulfur content, but the sulfur is present chiefly as sulfate in barite because of relatively high oxygen fugacity that prevails during deposit genesis. Sulfide mineral content of these veins is very low, and thus, potential for acid mine drainage generation is low. Thorium-bearing minerals in thorium-rare earth element veins are quite stable under natural conditions and tend to concentrate as detrital, relatively insoluble, even in low pH conditions, resistate minerals. Thorium complexing with various organic compounds may increase thorium-bearing mineral solubility, but thorium concentrations in natural water (pH 5 to 9) rarely exceed 1 ppb (Langmuir and Herman, 1980). Mining of most carbonatite dikes generally results in limited acid drainage generation, as well as minimal other environmental effects downstream because of the high acid buffering capacity of carbonate-rich ore.

Exploration geophysics

Alkaline intrusive complexes and carbonatite complexes, with which thorium-rare earth element veins and carbonatite dikes may be associated, have highly variable geophysical expressions that depend on their mineralogy, type of carbonatite stock, if present, intensity of host rock fenitization, and depth of weathering (Hoover, 1992). Some complexes contain major amounts of magnetite, ilmenite, and (or) perovskite, which result in positive magnetic anomalies. Abundant contained thorium- and uranium-bearing minerals, such as thorite, monazite, perovskite, and apatite may result in large positive radiometric anomalies. Gamma-ray spectrometry can quantitatively measure thorium, uranium, and potassium contents in veins and associated rocks. Detailed spectral data from remote sensing surveys can identify CO₂, ferrous iron, and rare earth elements associated with these deposits.

References

Dellwig (1951), Olson and others (1954), Kaiser (1956), Olson and Wallace (1956), Anderson (1958, 1981), Christman and others (1959), Hedlund and Olson (1961), Sharp and Cavender (1962), Staatz (1974, 1978, 1979,

1985), Staatz and others (1979, 1980), Armbrustmacher (1979, 1980, 1988), Olson and Hedlund (1981), and Thompson (1988).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Average deposit size is about 0.2 M metric tons of ore with a thorium-oxide grade of 0.4 weight percent (Bliss, 1992); these values are highly uncertain because none of the deposits have been mined to exhaustion. Most deposits are of low tonnage and high grade; associated environmental impact is limited because of their small size.

Host rocks

Alkaline intrusive rocks, granitic rocks, high-grade metamorphic rocks, aureoles surrounding alkaline intrusive complexes and fenitized carbonatite complexes, black shale, and novaculite are host rocks for thorium-rare earth element veins and carbonatite dikes.

Surrounding geologic terrane

Thorium-rare earth element veins and carbonatite dikes are frequently associated with alkaline intrusive complexes and carbonatite complexes. The majority of these complexes are located in relatively stable, intracratonic areas, but some are found close to tectonic plate margins and may be associated with orogenic rifting. Complexes are commonly located on major lithospheric domes or are related to major lineaments, or both. These complexes, typically mantle- or upper lithospheric-derived, intrude a wide variety of host rocks.

Wall-rock alteration

Thorium-rare earth element veins and carbonatite dikes are typically surrounded by, at most, several-m-wide aureoles of metasomatically altered rock. The process of alteration, fenitization, is caused by peralkaline fluids emanating from cooling alkaline silicate or carbonatite magmas. Fenitized aureoles surrounding veins and carbonatite dikes have limited geoenvironmental impact.

Nature of ore

Thorium-rare earth element veins and carbonatite dikes are structurally controlled. Veins and dikes directly associated with alkaline intrusive complexes and carbonatite complexes may occupy radial fractures, related to their host complexes. At other localities, fractures parallel to, and controlled by the dominant structural lineaments of the area, may be occupied by veins and dikes.

Deposit trace element geochemistry

Both veins and dikes contain primary enrichments of uranium, barium, strontium, lead, zinc, and niobium, as well as major amounts of thorium, rare earth elements, especially light rare earth elements, ferric iron oxide, silica, and sulfur as sulfate.

Ore and gangue mineralogy and zonation

The major ore minerals in thorium-rare earth mineral veins are thorite, thorianite, brockite, monazite, and a group of rare earth minerals including bastnaesite, parisite, synchysite, and similar rare earth carbonate minerals; sulfide minerals may be present but are rare. Gangue minerals include quartz, especially smoky quartz, potassium feldspar, barite, ferric iron oxide minerals, and trace amounts of galena and sphalerite. Many other minerals are found in specific deposits. Carbonatite dikes contain similar rare earth carbonate minerals and thorium-bearing minerals. Niobium-bearing minerals, especially pyrochlore and niobium-bearing rutile, may be abundant. Gangue minerals include calcite, dolomite, ankerite, siderite, sometimes strontianite, and other carbonate minerals. Allanite, monazite, magnetite, anatase, brookite, rutile, perovskite, barite, and a large number of additional minerals may be present.

Mineral characteristics

Thorium-rare earth mineral veins are chiefly quartz-barite veins with irregularly distributed thorium and rare earth minerals. In some veins, quartz and barite are coarse grained; euhedral smoky quartz lines vein walls and paragenetically later barite forms vein interiors. Other thorium-rich veins are fine grained; red, due to ferric iron oxide content; and have odoriferous fresh surfaces. Ore minerals are irregularly disseminated throughout carbonatite dikes.

Secondary mineralogy

Weathering of thorium-rare earth mineral vein and carbonatite deposits results in localized carbonate mineral dissolution.

Topography, physiography

These elongate, areally restricted deposits seem to have neither topographic nor physiographic expressions that are distinct.

Hydrology

The hydrologic regime is unaffected by thorium-rare earth element vein deposits, which are commonly small.

Mining and milling methods

Thorium-rare earth element vein deposits have been exploited only by very small-scale prospecting and mining. Workings generally consist of shallow surface pit and trench excavations. Very little if any ore from these operations has been milled.

ENVIRONMENTAL SIGNATURES

Drainage signatures

No data available. The facts that thorium-rare earth element vein deposits contain very low sulfide mineral abundances and consist of low-solubility, resistate minerals suggests that these veins contribute insignificantly to the geochemistry of water draining these deposits.

Metal mobility from solid mine wastes

Thorium-bearing minerals tend to have low solubility and form deposits of resistate minerals; metal mobility from solid mine waste associated with thorium-rare earth element vein deposits is consequently very limited.

Soil, sediment signatures prior to mining

Stream-sediment samples collected for the NURE study of the Pueblo 1°x2° quadrangle, Colo., failed to identify the Wet Mountains thorium district. Thus, it appears that thorium-bearing minerals do not widely disperse, and that geochemical haloes associated with thorium deposits are small. More detailed surveys would probably show that thorium abundances in soil near thorium-rare earth element vein deposits are elevated. Residual soil can contain elemental suites similar to those in underlying deposits.

Potential environmental concerns associated with mineral processing

Neither thorium-rare earth mineral vein nor carbonatite deposits are likely to have significant associated natural or mine-related acid drainage. Unless all thorium is recovered during mining and milling, waste dumps and tailings contain radioactive materials. Fertilized rocks surrounding these deposits contain anomalous amounts of radioactive minerals that might pose an environmental hazard in associated waste dumps.

Smelter signatures

The absence of significant ore having been produced from thorium-rare earth element vein deposits precludes environmental impact attributable to smelting.

Climate effects on environmental signatures

The effects of various climatic regimes on the geoenvironmental signature specific to thorium-rare earth element veins deposits are not known. Because most of these deposits have relatively low sulfide mineral contents environmental signatures associated with thorium-rare earth element vein deposits probably are not much affected by climatic regime variation. Dispersal of radioactive solid waste associated with deposits in areas with high precipitation may be more widespread as a function of increased surface runoff.

Geoenvironmental geophysics

Egress of radioactive particles from mine areas and waste dumps can be identified and monitored by gamma-ray spectrometry or total count scintillometers; detailed airborne or ground-based surveys can be employed, depending on the type of coverage that is warranted.

REFERENCES CITED

- Anderson, A.L., 1958, Uranium, thorium, columbium, and rare earth deposits in the Salmon region, Lemhi County, Idaho: Idaho Bureau of Mines and Geology Pamphlet, v. 115, p.
- Anderson, J.M., 1981, The origin of rare earth, thorium, and uranium mineralization in the northern Tendoy Mountains, Beaverhead County, Montana: Bellingham, Western Washington University, M.S. thesis, 101 p.
- Armbrustmacher, T.J., 1979, Replacement and primary magmatic carbonatites from the Wet Mountains area, Fremont and Custer Counties, Colorado: *Economic Geology*, v. 74, p. 888-901.
- _____, 1980, Abundance and distribution of thorium in the carbonatite stock at Iron Hill, Powderhorn district, Gunnison County, Colorado: U.S. Geological Survey Professional Paper 1049-B, p. B1-B11.
- _____, 1988, Geology and resources of thorium and associated elements in the Wet Mountains area, Fremont and Custer Counties, Colorado: U.S. Geological Survey Professional Paper 1049-F, 34 p.
- Bliss, J.D., 1992, Developments in mineral deposit modeling: U.S. Geological Survey Bulletin 2004, 168 p.
- Christman, R.A., Brock, M.R., Pearson, R.C. and Singewald, Q.D., 1959, Geology and thorium deposits of the Wet Mountains, Colorado: a progress report: U.S. Geological Survey Bulletin, 1072-H, p. 491-535.
- Dellwig, L.F., 1951, Preliminary summary report on the Wet Mountains thorium area, Custer and Fremont Counties, Colorado: U.S. Geological Survey Trace Elements Memorandum Report, v. 287, 13 p.
- Hedlund, D.C. and Olson, J.C., 1961, Four environments of thorium-, niobium-, and rare-earth-bearing minerals in the Powderhorn district of southwestern Colorado: U.S. Geological Survey Professional Paper 424-B, p. B283-B286.
- Hoover, D.B., compiler, 1992, Geophysical model of carbonatite, *in* Hoover, D.B., Heran, W.D., and Hill, P.L., eds., The geophysical expression of selected mineral deposit models: U.S. Geological Survey Open-File Report 92-557, p. 80-84.
- Kaiser, E.P., 1956, Preliminary report on the geology and deposits of monazite, thorite, and niobium-bearing rutile of the Mineral Hill district, Lemhi County, Idaho: U.S. Geological Survey Open-File Report 56-69, 41 p.
- Langmuir, Donald, and Herman, J.S., 1980, The mobility of thorium in natural waters at low temperatures: *Geochimica et Cosmochimica Acta*, v. 44, p. 1753-1766.
- Olson, J.C. and Hedlund, D.C., 1981, Alkalic rocks and resources of thorium and associated elements in the Powderhorn district, Gunnison County, Colorado: U.S. Geological Survey Professional Paper 1049-C, 34 p.
- Olson, J.C., Shawe, D.R., Pray, L.C., and Sharp, W.N., 1954, Rare-earth deposits of the Mountain Pass district, San Bernardino County, California: U.S. Geological Survey Professional Paper 261, 75 p.
- Olson, J.C. and Wallace, S.R., 1956, Thorium and rare-earth minerals in Powderhorn district, Gunnison County, Colorado: U.S. Geological Survey Bulletin 1027-O, p. 693-723.
- Sharp, W.N. and Cavender, W.S., 1962, Geology and thorium-bearing deposits of the Lemhi Pass area, Lemhi County, Idaho, and Beaverhead County, Montana: U.S. Geological Survey Bulletin, 1126, 76 p.
- Statz, M.H., 1974, Thorium veins in the United States: *Economic Geology*, v. 69, p. 494-507.
- _____, 1978, I and L uranium and thorium vein system, Bokan Mountain, southeastern Alaska: *Economic Geology*, v. 73, p. 512-523.
- _____, 1979, Geology and mineral resources of the Lemhi Pass thorium district, Idaho and Montana: U.S. Geological Survey Professional Paper 1049-A, 90 p.
- _____, 1985, Geology and description of the thorium and rare-earth veins in the Laughlin Peak area, Colfax County, New Mexico: U.S. Geological Survey Professional Paper 1049-E, p. E1-E32.
- _____, 1992, Descriptive model of thorium-rare-earth veins, *in* Bliss, J.D., ed., Developments in mineral deposit modeling: U.S. Geological Survey Bulletin 2004, p. 13-15.
- Statz, M.H., Armbrustmacher, T.J., Olson, J.C., Brownfield, I.K., Brock, M.R., Lemons, J.F., Jr., Coppa, L.V., and Clingan, B.V., 1979, Principal thorium resources in the United States: U.S. Geological Survey Circular 805, 42 p.
- Statz, M.H., Hall, R.B., Macke, D.L., Armbrustmacher, T.J., and Brownfield, I.K., 1980, Thorium resources of selected regions in the United States: U.S. Geological Survey Circular 824, 32 p.
- Thompson, T.B., 1988, Geology and uranium-thorium mineral deposits of the Bokan Mountain granite complex, southeastern Alaska: *Ore Geology Reviews*, v. 3, p. 193-210.

SN AND (OR) W SKARN AND REPLACEMENT DEPOSITS (MODELS 14a-c; Cox, 1986; Reed and Cox, 1986; Reed, 1986)

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SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

See general comments in section entitled "Introduction" in CU, AU, ZN-PB skarn deposits model (Hammarstrom and others, this volume).

Deposit geology

These deposits consist of tin, tungsten, and beryllium minerals in skarns, veins, stockworks, stratabound replacement deposits, and greisens in carbonate rocks at or near granite contacts.

Examples

Tungsten skarns: Pine Creek Mine, Calif.; Mill City district, Nev.; Rock Creek district, Mont.; Mactung, Northwest Territories, Canada.

Tin skarns: Lost River, Alaska; Moina, Tasmania, Australia.

Tin replacement deposits: Renison Bell, Tasmania, Australia; Dachang, Guangxi, China.

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include zinc skarns (Model 18c), tin greisens (Model 15c), and quartz-cassiterite-sulfide mineral veins, quartz-tourmaline-cassiterite veins, and (or) tin-tungsten-molybdenum stockworks (Model 15b). See Vein and greisen SN and W deposits model (Elliott and others, this volume).

Potential environmental considerations

These deposits have low acid drainage generation potential relative to many other deposit types because of their generally low sulfide mineral content, relatively small deposit size, low impact mining and milling methods (relative to many other mineral deposit types), and abundance of associated carbonate rocks, which can buffer any acid drainage generated as a consequence of sulfide mineral oxidation. However, some tin replacement deposits and some tungsten skarns (for example, Mactung, Cantung; Canada) have sulfide-mineral-rich zones that may have significant acid generation potential. Both tungsten and tin are present along with fluorine and beryllium in some skarn deposits.

Exploration geophysics

In exploration, geophysics is principally used to define associated highly differentiated leucogranites by their relatively weak magnetic response, low density, and high radioelement content (Hoover and Knepper, 1992). Magnetic and induced polarization surveys can be used to outline the surface projection of orebodies because magnetite, pyrrhotite, and other sulfide minerals are common in these deposits. Although skarns typically have a positive density contrast relative to adjacent intrusions and carbonate rocks, gravity surveys are not commonly used due to their relatively high cost and non-specificity for ore. Remote sensing techniques can effectively identify carbonate terranes and iron enrichment in skarns if skarn is exposed. In some cases, contacts between intrusions and sedimentary rocks can be mapped and carbonate rocks can be distinguished from non-carbonate rocks.

References

Geology: Hepworth and Zhang (1982), Cox (1986), Reed (1986), Reed and Cox (1986).

Environmental geology: Sainsbury and others (1968).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Menzie and Reed (1986a,b) and Menzie and others (1992) present the following deposit size ranges, in millions of tonnes (tonnes=1 metric ton=1.102 short tons), expressed as percentiles of tonnage, for populations of N deposits:

W skarns (N=36)-	0.04 (90th percentile)	0.80 (50th percentile)	18 (10th percentile)
Sn skarns (N= 4)-	1.6 (90th percentile)	9.4 (50th percentile)	58 (10th percentile)
Replacement Sn (N=6)-	1.0 (90th percentile)	5.2 (50th percentile)	27 (10th percentile)

The 50th percentile value is the median deposit size for each population. Most recent world production has been from relatively large deposits (10 million metric tons or more). The strategic mineral value of tungsten led to government subsidized mining of many small deposits (on the order of 1 million t or less) during World Wars I and II and the Korean War primarily in the western United States.

Host rocks

These deposits are hosted by carbonate rock, including limestone, dolomite, marble, and carbonate-bearing pelite, argillite, and shale. In terms of Glass and others' (1982) classification of bedrock types, most host rocks for these deposit types are type IV, that is, they are highly calcareous sedimentary rocks or metamorphosed calcareous sedimentary rocks that have extensive buffering capacity.

Surrounding geologic terrane

These deposits are typically associated with contact zones around relatively evolved granite stocks, plutons, or batholiths; cogenetic volcanic rocks are generally absent.

Wall-rock alteration

Wall-rock alteration commonly includes extensive greisen development and sericitic and silicic alteration (Kotlyar and others, 1995). Intrusive rocks associated with tungsten skarns may be altered to an endoskarn assemblage, which consists of mica, calcite, and pyrite.

Nature of ore

Tungsten skarn orebodies are stratiform deposits that can extend for hundreds of meters along lithologic contacts. Stockwork and local crosscutting veins are common. The grain size and molybdenum content of scheelite in tungsten skarns varies. Paragenetically early, anhydrous skarn generally contains relatively fine-grained, high-molybdenum scheelite, whereas retrograde skarn contains medium to coarse grained low-molybdenum scheelite. Coarse grained, vuggy skarn with uneven ore grades forms from impure marble; finer-grained, compact skarns with more evenly distributed ore grades tend to form from pure marbles (Einaudi and others, 1981).

Cassiterite in tin skarns is commonly very fine grained. Tin concentrations range from 0.1 to 1 weight percent in deposits that include 10 to 90 million tonnes of ore. Tin may be contained in silicate minerals, including garnet and hornblende (Eadington, 1983).

Deposit trace element geochemistry

W skarns- W, Mo, Zn, Cu, Sn, Bi, As, Fe, Mn.

Sn skarns- Sn, W, F, Be, Zn, Cu, Ag, Li, Rb, Cs, Re, B.

Replacement Sn- Sn, As, Cu, B, W, F, Li, Pb, Zn, Rb.

See tables 1-4 for examples of ranges of geochemical signatures associated with rock, stream sediment, and soil samples from these deposit types; also see Beus and Grigorian (1977) for additional trace element data pertaining to these deposits.

Ore and gangue mineralogy and zonation

Skarn deposits exhibit temporal and spatial zoning that reflect stages of skarn development. Early formed prograde mineral assemblages are overprinted and crosscut by retrograde mineral assemblages to varying degrees. Initial metamorphism forms marble and hornfels. Subsequent metasomatism forms high-temperature anhydrous calcsilicate minerals that may be overprinted or cut by later, lower temperature hydrous mineral assemblages. Although the principal ore minerals in tungsten and tin deposits are generally not sulfide minerals, a variety of sulfide minerals can be present in these deposits. Sulfide minerals are generally deposited with late hydrous minerals.

In tungsten skarns, scheelite is deposited near the marble front during early prograde metasomatism but is generally remobilized and redeposited in coarse-grained, high-grade masses with sulfide minerals in zones of hydrous alteration. In tungsten-tin skarns, tungsten is concentrated proximal to intrusive rock, whereas tin is concentrated in more distal parts of skarns (for example, Shizhuyuan, China). In some cases, sulfide minerals are present close to intrusive contacts (for example, Black Rock, Calif.).

Tin skarns may be calcic or magnesian. Calcic tin skarns may be enriched in magnetite. Cassiterite is concentrated residually in oxidized parts of lode deposits, especially if deposited with sulfide minerals. In tin skarns, tin may be present in titanite (sphene), andradite, and grossular. Many other tin silicate, sulfide, and borate minerals

Table 1. Summary ranges of analytical data for 20 samples of skarn from the Lentung W skarn deposit, Rock Creek district, Mont. (data from DeBoer, 1991).

[Samples represent garnet-pyroxene skarn ± scheelite and chalcopyrite. Methods include DCP, ICP, AA, INAA for W. Sn was analyzed, but not detected in any of the samples. Concentrations reported as ppm, unless otherwise indicated. N= number of samples in which the element was detected. See DeBoer (1991) for detection limits and details of analyses; --, not detected]

Element	N	Minimum	Maximum	Mean
Au (ppb)	1	11	11	11
Ag	18	.5	151	10.4
Al (%)	20	.2	224	13.7
As	13	7	55	36
Ba	20	1	212	25
Be	11	0.6	6.5	2.5
Bi	16	--	130	31
Ca (%)	2	4.32	7.44	5.88
Cd	4	1	21	9
Ce	20	7	153	91
Co	20	4	54	18
Cr	20	10	237	82.2
Cu	20	2	6,005	411.4
Fe (%)	8	2.08	9.74	6.17
Ga	14	3	25	12
Hg (ppb)	20	15	50	22
K (%)	4	.05	0.65	0.32
La	13	2	114	28
Li	20	3	49	12
Mg (%)	19	.13	6.12	2.32
Mn	18	1,868	19,460	8,610
Mo	20	8	1,214	176
Na (%)	20	.1	2.26	0.33
Nb	20	5	44	14
Ni	20	15	59	42
Pb	15	4	11,100	798
Rb	6	33	642	286
Sb	14	6	42	18
Sc	16	26	133	70
Sr	20	8	626	86
Ta	20	28	230	114
Th	15	11	55	28
Ti (%)	19	.02	0.65	0.22
V	20	17	352	144
W	18	15	3,200	620
Y	20	4	46	19
Zn	20	16	954	183
Zr	20	13	229	106

have been identified in skarns; stannite (Cu_2FeSnS_4) is the most important of these.

In the tungsten-tin-fluorine calcic skarns at the Mt. Lindsay deposit (Tasmania), sulfide skarn with low tin content formed near the contact between carbonate rocks and igneous rocks. Cassiterite-rich magnetite skarn formed in the distal parts of the skarn near unreplaced marble. During intermediate stages of skarn formation, cassiterite reacted completely to produce tin-bearing silicate minerals such as titanite, amphibole, and ilvaite (Kwak, 1983).

W skarns: Prograde- Pyroxene (diopside-hedenbergite), garnet (grossular-andradite), idocrase, wollastonite.
 Retrograde- Spessartine-rich garnet, biotite, amphibole, plagioclase, epidote, quartz, chlorite, sulfide minerals (chalcopyrite, pyrite, pyrrhotite, sphalerite, bornite, arsenopyrite, bismuthinite), magnetite, fluorite, native bismuth.
 Ore- Scheelite, molybdenite, wolframite, cassiterite.

Table 2. Summary ranges of analytical data for samples of skarn, endoskarn, hornfels, marble, and jasperoid associated with skarn in the Tonopah 1°x2° quadrangle, Nev. [Concentrations reported as ppm; N, number of samples in which element was detected; detection limits for each element are given in parentheses. Unpublished emission spectrographic data for rock samples from Lodi Hills, Ellsworth, Cedar Mountain, Peg Leg Mine (San Antonio Mountains), Timblin Canyon in the Toiyabe Range, and the Victory W mine; D.A. John]

Element	N	Minimum	Maximum	Mean
As (200)	1	1,000	1,000	1,000
Be (1)	30	1	65	11
Bi (20)	6	10	500	143
Cd (20)	1	100	100	100
Cu (5)	27	5	7,000	356
Mo (5)	19	7	700	63
Pb (10)	38	10	20,000	1,054
Sb (100)	4	20	300	130
Sn (10)	16	10	200	56
W (50)	11	50	10,000	1,563
Zn (200)	14	200	10,000	2,686

Table 3. Summary ranges of trace element contents, in parts per million, for selected stream sediment samples from the Sn-W-Be district of the Seward Peninsula, Alaska (data from Sainsbury and others, 1968).

[Spectrograph and spectrophotometric data for 17 stream sediment samples from 13 drainages. N, number of samples in which the element was detected. See Sainsbury and others (1968) Table 1 for detection limits and Table 8 for descriptions of methods and samples]

Element	N	Minimum	Maximum	Mean
As	2	1,500	3,000	2,250
B	11	15	700	185
Be	12	3	160	45
Cu	17	7	150	34
Li	9	15	3,000	713
Nb	3	15	15	15
Pb	11	15	150	64
Sn	13	10	1,100	148
W	6	10	70	38
Zn	1	300	300	300

- Sn skarns: Prograde- Idocrase, garnet (spessartine-rich grandite, tin-bearing andradite), malayite, danburite, datolite, pyroxene, wollastonite.
 Retrograde- Amphibole, mica, epidote, magnetite, chlorite, tourmaline, fluorite, sulfide minerals (sphalerite, pyrrhotite, chalcopyrite, pyrite, arsenopyrite), Be minerals (helvite, danalite).
 Ore- Cassiterite, scheelite.
- Replacement Sn: Major minerals- Cassiterite, pyrrhotite, chalcopyrite, pyrite, arsenopyrite, ilmenite, fluorite.
 Minor minerals- Pyrite, sphalerite, galena, stannite, tetrahedrite, magnetite.
 Late veins- Sphalerite, galena, chalcopyrite, pyrite, fluorite.

Table 4. Summary ranges of trace element contents for soil associated with the Sn-W-Be district of the Seward Peninsula in the Lost River valley, Alaska (data from Sainsbury and others, 1968). [Selected AA, spectrophotometric, and SQS for 40 soil samples. N, number of samples in which the element was detected. Li present, in undetermined amount, in 37 samples. See Sainsbury and others (1968) Table 9 for detailed description of samples and methods and Table 1 for detection limits. Minimum, maximum, and mean concentrations in parts per million]

Element	N	Minimum	Maximum	Mean
As	9	1,500	2,000	1,611
B	37	30	200	104
Be	32	2	270	74
Cu	40	16	610	92
Nb	32	0	30	19
Pb	40	35	2,100	448
Sn	37	10	1,500	210
Zn	40	50	5,000	1,074

Mineral characteristics

Tin ore at the Renison Bell, Tasmania, replacement tin deposit consists of fine-grained (<150 micron) cassiterite closely associated with sulfide minerals (pyrrhotite, as well as minor chalcopyrite, pyrite, arsenopyrite, marcasite, sphalerite, and galena) in silicate-carbonate gangue.

Secondary mineralogy

Cassiterite, the primary ore mineral of tin, is very stable under most near-surface conditions and its dispersion is dependent more on physical than chemical conditions. However, cassiterite-plus-sulfide skarns in humid climates readily decompose, but cassiterite-quartz-tourmaline assemblages form residual soil overlying deposits. Oxidation can cause the formation of varlamoffite, a soft, earthy, impure hydrated stannic oxide that is less inert than cassiterite. Readily dissolved varlamoffite can release tin into solution.

Topography, physiography

Granitoid plutons associated with skarn tend to form positive areas of moderate to high relief. However, in semi-arid environments subjected to extended periods of weathering, some granitoid plutons may occupy topographic lows. Silicified rocks associated with skarns may form knobs or ridges.

Hydrology

Tungsten skarns are associated with largely unfractured plutons. Post-mineralization faults may focus ground water flow in underground workings.

Mining and milling methods

These deposits have been mined by open pit and underground methods.

W skarns: Mining method generally depends on the grade and form of the deposit; higher average ore grades (0.7 weight percent WO_3 or more) are generally required to warrant costs of underground mining operations. Underground methods include room-and-pillar (Cantung, British Columbia; King Island, Australia), cut-and-fill, stoping (Pine Creek, Calif.) or combinations of these methods (Anstett and others, 1985). Gravity, flotation, and chemical methods are used to produce natural and artificial scheelite, and ammonium paratungstate (APT) (Smith, 1994).

Scheelite concentrate has been produced in the United States using gravity, flotation, and magnetic separation techniques (Stager and Tingley, 1988). After crushing and grinding, sulfide minerals and scheelite are separated by flotation, and sulfide slimes are removed to tailings piles. Scheelite concentrates are processed to precipitate silica. Molybdenum is removed as MoS_3 via a precipitation process that releases H_2S through scrubber-equipped stacks. An organic solvent extraction technique is used to produce APT.

Sn skarns: Cut and fill stoping methods are used at the Renison Bell, Tasmania, replacement tin deposit, the world's largest underground mine. Sulfide-mineral-rich and sulfide-mineral-poor ore are selectively stockpiled on the surface and blended ore is fed into a three-stage open crushing circuit that reduces ore from 750 mm to 15 mm. Ore is processed by flotation to remove sulfide minerals prior to gravity concentration of cassiterite (Morland, 1986). Staged grinding is used to liberate fine-grained cassiterite. Residual sulfide minerals in the gravity concentrate are removed by flotation. Cassiterite concentrates are leached with sulfuric acid to remove siderite, magnetic material is removed using magnetic separators; refined concentrates are then shipped to smelters. Tailings are combined with lime to adjust pH to 8.5 before being pumped to impoundments.

ENVIRONMENTAL SIGNATURES

Surface disturbance

Mining these deposits may result in associated open pits, tailings piles, and subsidence in areas of underground mining.

Drainage signatures

The mobility of tungsten (probable aqueous species is HWO_4^-) is intermediate to low at normal pH. Tungsten is known to be present in aqueous solution in alkaline lakes.

W skarns: No data; most deposits studied in the Basin and Range do not have stream drainages. Water is probably well buffered by carbonate minerals but may contain elevated abundances of arsenic, zinc, molybdenum, tungsten, or uranium. Spring water discharged from a travertine spring terrace and Quaternary sand and gravel associated with tungsten skarns and epithermal manganese-tungsten deposits in the Rose Creek district, Pershing Co., Nev. contains as much as 0.3 weight percent WO_3 and 9 weight percent manganese, and has a pH of 6.4 and specific conductance of 2,690 micromhos (White and others, 1963, Table 23).

Sn skarns: Beryllium has not been detected in natural water of southwest Alaska where many of these deposits are present; tin abundances are also probably extremely low. Tin concentrations in fresh ground water and thermal water are $\leq 1 \mu\text{g/l}$; in oilfield brines, concentrations are as much as $670 \mu\text{g/l}$ (Forstner and Wittman, 1981). As demonstrated by hydromorphic dispersion anomalies associated with disseminated gold deposits in Nevada (Grimes and others, 1995), where ground water tungsten concentrations are 1 to $260 \mu\text{g/l}$, tungsten can be mobile in ground water. However, the greatest tungsten concentrations are in samples for which Eh and arsenic speciation indicates reducing conditions associated with carbonaceous black shale host rocks.

Metal mobility from solid mine wastes

Tungsten: No data.

Tin: The mobility of tin from cassiterite is generally low because cassiterite is very stable in the surface environment. Cassiterite is probably the principal tin phase in soil. Evolved granites associated with tin skarn and the skarns themselves contain elevated fluorine concentrations because of their fluorite abundances. In the granitic terranes of India, high fluorine abundances in water and soil are associated with the incidence of fluorosis in humans and livestock (Karunakaran, 1977). Although most public water supplies in the United States are fluoridated ($\leq 1 \text{ ppm}$), to inhibit dental cavity formation, elevated fluorine concentrations ($> 2 \text{ ppm}$) may cause fluorosis; in warm climates lower concentrations may pose problems (Minoguchi, 1977). Fluorite in greisen and fluorite-beryllium zones associated with tin skarns may provide geoavailable fluorine and beryllium.

Soil, sediment signatures prior to mining

The geochemical database for the Tonopah $1^\circ \times 2^\circ$ quadrangle, Nev., showed strong anomalies in Ag, As, Bi, Cd, Cu, Mo, Pb, Sb, W, and Zn in many places. The lead-zinc-antimony-arsenic signature appears to be associated with cross-cutting polymetallic veins peripheral to associated skarn deposits (Nash, 1988). Stream sediment samples from drainages associated with this deposit type have geochemical signatures that are similar to those of ore samples, but contain lower concentrations due to dilution. In the Great Basin, sedimentary transport causes scheelite to mechanically disintegrate to very fine grain sizes within about 3 km of its source.

Potential environmental concerns associated with mineral processing

Processing tungsten and tin ore probably poses fewer problems than those associated with most other ore types. No tungsten compounds are included as toxic substances on U.S. Environmental Protection Agency (EPA) toxic release inventory lists (Smith, 1994). However, elevated fluorite abundances associated with some tin skarn deposits suggest that particulate emissions may pose environmental hazards.

Smelter signatures

The preferred method of tin ore beneficiation (fuming, smelting, or refining) depends on tin grade and content of iron and other impurities (Bleiwas and others, 1986). Fuming and smelting may release sulfur and arsenic.

Climate effects on environmental signatures

The effects of various climatic regimes on the geoenvironmental signature specific to these deposits are not known. Because most of these deposits have relatively low sulfide mineral contents and because carbonate minerals that have abundant acid consumption potential are abundant in association with these deposits, environmental signatures associated with tin and (or) tungsten skarn and replacement deposits are probably not much affected by climatic regime variation. Both scheelite and cassiterite are resistant minerals and their tungsten and tin contents are relatively immobile within a range of surficial weathering regimes.

Geoenvironmental geophysics

For those deposits where sulfide mineral oxidation may present hazards, induced polarization surveys can provide an estimate of sulfide mineral abundances in unmined ore or in solid mine waste. A combination of induced polarization, electromagnetic, and direct-current resistivity surveys can help trace the source and flow of acid water associated with sulfide mineral oxidation. Although no longer commercially available, the airborne UV-laser induced fluorescence method (Luminex) provides a rapid and sensitive method that may have application to identification of dispersed waste trains via direct scheelite identification.

Remote sensing methods can delineate the extent of altered rock and define iron oxide mineral distributions. Plant density variations and growth vigor (stress) related to metal release and smelter plumes can be delineated with multispectral reflectance imaging methods, but stress caused by toxic elements or acid drainage and that from lack of water or other factors cannot be distinguished. New applications of airborne imaging spectroscopy data from NASA's Airborne Visible and Infrared Imaging Spectrometer may hold great potential for mapping environmental contamination on a regional scale by identifying surface distributions of various minerals on the basis of reflectance differences due to slight changes in chemistry and crystal structure (Clark and others, 1993; King and others, 1994).

Effects of metals associated with these deposits types on life

Plants: Tin is not a known plant nutrient, but is known to become concentrated in plants growing in tin-enriched soil.
Animals: Animal studies suggest that ingested tungsten is either nonabsorbed and excreted or rapidly excreted and of the trace elements identified in coal, tungsten is the least toxic to a variety of fish species (Smith, 1994).
Humans: Tungsten is not known to be toxic to humans (no documented cases of tungsten poisoning) and no tungsten compounds have been included in the EPA's toxic release inventory list (Smith, 1994).

PERSPECTIVE

See section entitled "Perspective" in CU, AU, ZN-PB skarn deposits model (Hammarstrom and others, this volume).

REFERENCES CITED

- Anstett, T.F., Bleiwas, D.I., and Hurdelbrink, R.J., 1985, Tungsten availability-Market economy countries: U.S. Bureau of Mines Information Circular 9025.
- Beus, A.A., and Grigorian, S.V., 1977, Geochemical exploration methods for mineral deposits: Wilmette, Illinois, Applied Publishing Ltd., 287 p.
- Bleiwas, Donald I., Sabin, Andrew E., and Peterson, Gary R., 1986, Tin availability-Market economy countries, A minerals availability program appraisal: U.S. Bureau of Mines Information Circular 90-86, 50 p.
- Clark, R.N., Swayze, G.A., and Gallagher, Andrea, 1993, Mapping minerals with imaging spectroscopy, *in* Scott, R.W., Jr., and others, eds., Advances related to United States and international mineral resources--Developing frameworks and exploration techniques: U.S. Geological Survey Bulletin 2039, p. 141-150.
- Cox, D.P., 1986, Descriptive model of W skarn deposits, *in* Cox, D.P. and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 55.
- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- DeBoer, Thomas A., 1991, Geology and mineralization of the Lentung tungsten skarn deposit near Brownes Lake, Pioneer Mountains, Montana: Bellingham, Western Washington University, M.S. thesis, 200 p.
- Eadington, P.J., 1983, Geochemical exploration for tin-recent research results *in* Smith, R.E., ed., Geochemical exploration in deeply weathered terrain, CSIRO.

- Einaudi, M.T., Meinert, L.D., and Newberry, R.J., 1981, Skarn deposits: Economic Geology 75th Anniversary Volume, p. 317-391.
- Forstner, U., and Wittmann, G.T.W., 1981, Metal pollution in the aquatic environment: New York, Springer-Verlag, 486 p.
- Glass, N.R., Arnold, D.E., Galloway, J.N., Henry, G.R., Lee, J.J., McFee, N.W., Norton, S.A., Powers, C.F., Rambo, D.L., and Schofield, C.L., 1982, Effects of acid precipitation: Environmental Science and Technology, v. 15, p. 162A-169A.
- Grimes, D.J., Ficklin, W.H., Meier, A.L., and McHugh, J.B., 1995, Anomalous gold, arsenic, antimony and tungsten in ground water and alluvium around disseminated gold deposits along the Getchell trend, Humboldt County, Nevada: Journal of Geochemical Exploration, v. 52, p. 351-371.
- Hepworth, J.V., and Zhang, Y.H., Eds., 1982, Tungsten Geology, Jiangxi, China (Proceedings of a Symposium jointly sponsored by the ESCAP/RMRDC and Ministry of Geology, People's Republic of China, 12-22 October 1981): Bandung, Indonesia, ESCAP/RMRDC, 583 p.
- Hoover, D.B., and Knepper, D.H., 1992, Geophysical model of a tin skarn and related deposits, in Hoover, D.B., Heran, W.D., and Hill, P.L., eds., The geophysical expression of selected mineral deposit models: U.S. Geological Survey Open-File Report 92-557, p. 89-94.
- Karunakaran, C., 1977, Fluorine-bearing minerals in India-their geology, mineralogy, and geochemistry, in Proceedings of the symposium on fluorosis, Indian Academy of Geosciences, Hyderabad, p. 3-18.
- King, T.V.V., Ager, Cathy, Clark, R.N., Swayze, G.A., and Gallagher, A.J., 1994, Application of field and laboratory spectroscopic analysis to investigate the environmental impact of mining in the southeastern San Juan Mountains and adjacent San Luis Valley, Colorado: U.S. Geological Circular 1103-A, p. 53-54.
- Kotlyar, B.B., Ludington, Steve, and Mosier, D.L., 1995, Descriptive, grade, and tonnage models for molybdenum-tungsten greisen deposits: U.S. Geological Survey Open-File Report 95-584, 30 p.
- Kwak, T. A.P., 1983, The geology and geochemistry of the zoned, Sn-W-F-Be skarns at Mt. Lindsay, Tasmania, Australia: Economic Geology, v. 78, p. 1440-1465.
- Menzie, W.D., and Reed, B.L., 1986a, Grade and tonnage model of Sn skarn deposits, in Cox, D.P. and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 58-60.
- _____ 1986b, Grade and tonnage model of replacement Sn, in Cox, D.P. and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 62-63.
- Menzie, W.D., Jones, G.M., and Elliott, J.E., 1992, Tungsten-Grades and tonnages of some deposits, in DeYoung, J.H., Jr., and Hammarstrom, J.M., eds., Contributions to commodity geology research: U.S. Geological Survey Bulletin 1877, p. J1-J7.
- Minoguchi, Gen, 1977, The correlation of chronic toxic effect in tropical and subtropical areas between fluoride concentration in drinking water and climate, especially mean annual temperature, in Proceedings of the symposium on fluorosis, Indian Academy of Geosciences, Hyderabad, p. 175-186.
- Morland, R., compiler, 1986, Renison Bell tin mine-technical review: Unpublished report from Renison Limited, 32 p.
- Nash, J.T., 1988, Interpretation of the regional geochemistry of the Tonopah 1°x2° quadrangle, Nevada, based on analytical results for stream-sediment and nonmagnetic heavy-mineral concentrate samples: U.S. Geological Survey Bulletin 1849, 28 p.
- Reed, B.L., 1986, Descriptive model of replacement Sn, in Cox, D.P. and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 61.
- Reed, B.L., and Cox, D.P., 1986, Descriptive model of Sn skarn deposits, in Cox, D.P. and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 58.
- Sainsbury, C.L., Hamilton, J.C., and Huffman, Claude, Jr., 1968, Geochemical cycle of selected trace elements in the tin-tungsten-beryllium district, western Seward Peninsula, Alaska--a reconnaissance study: U.S. Geological Survey Bulletin 1242-F, p. F1-F42.
- Smith, Gerald R., 1994, Materials flow of tungsten in the United States: U.S. Bureau of Mines Information Circular 9388.
- Stager, H.K., and Tingley, J., 1988, Tungsten deposits in Nevada: Nevada Bureau of Mines and Geology Bulletin 105, 256 p.
- White, Donald E., Hem, John D., and Waring, G.A., 1963, Data of Geochemistry, Sixth Edition, Chapter F. Chemical composition of subsurface waters: U.S. Geological Survey Professional Paper 440-F, 67 p.

VEIN AND GREISEN SN AND W DEPOSITS
(MODELS 15a-c; Cox and Bagby, 1986; Reed, 1986a,b)

by James E. Elliott, Robert J. Kamilli, William R. Miller, and K. Eric Livo

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Vein deposits consist of simple to complex fissure filling or replacement quartz veins, including discrete single veins, swarms or systems of veins, or vein stockworks, that contain mainly wolframite series minerals (huebnerite-ferberite) and (or) cassiterite as ore minerals (fig. 1). Other common minerals are scheelite, molybdenite, bismuthinite, base-metal sulfide minerals, tetrahedrite, pyrite, arsenopyrite, stannite, native bismuth, bismuthinite, fluorite, muscovite, biotite, feldspar, beryl, tourmaline, topaz, and chlorite (fig. 2). Complex uranium, thorium, rare earth element oxide minerals and phosphate minerals may be present in minor amounts. Greisen deposits consist of disseminated cassiterite and cassiterite-bearing veinlets, stockworks, lenses, pipes, and breccia (fig. 3) in gangue composed of quartz, mica, fluorite, and topaz. Veins and greisen deposits are found within or near highly evolved, rare-metal enriched plutonic rocks, especially near contacts with surrounding country rock; settings in or adjacent to cupolas of granitic batholiths are particularly favorable.

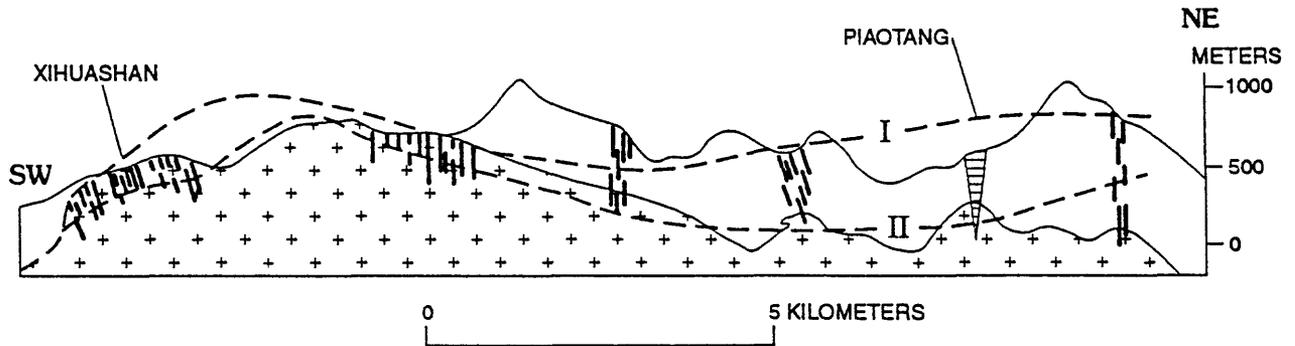


Figure 1. Generalized longitudinal section through the Xihuashan and Piaotang tungsten deposits in the Dayu district, China. Other vein systems are indicated by heavy lines. I, upper limits of ore zones; II, lower limits of ore zones. Patterned area is granite batholith. Unpatterned area is sedimentary and metamorphic rocks (from Elliott, 1992).

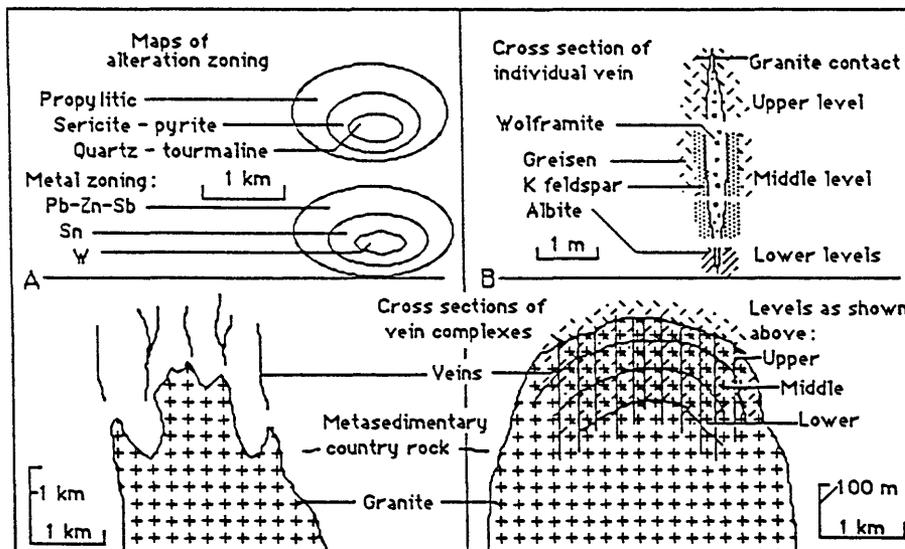


Figure 2. Maps and sections of tungsten vein deposits illustrating mineral and alteration zoning. A, Chicote Grande deposit, Bolivia; B, Xihuashan, China (from Cox and Bagby, 1986).

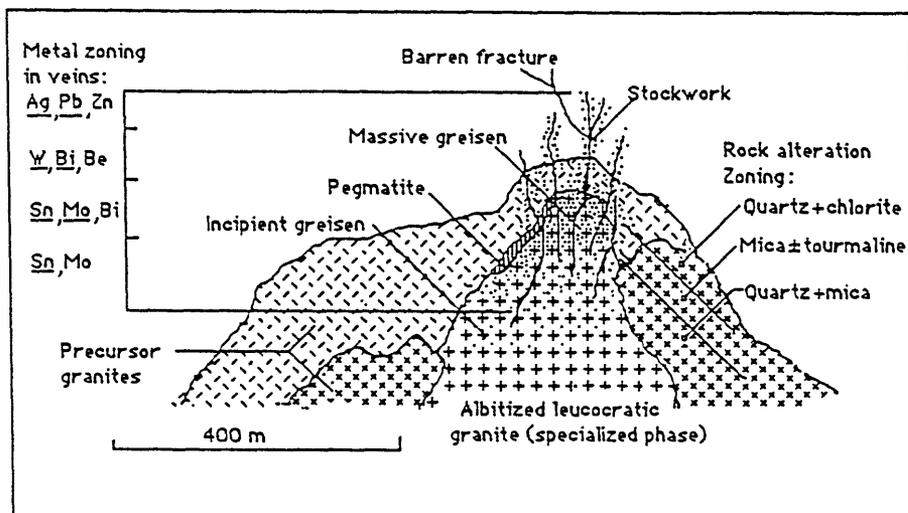


Figure 3. Diagrammatic cross section of a tin greisen (from Reed, 1986b).

Examples

Pasto Bueno, Peru (Landis and Rye, 1974); Panasqueira, Portugal (Kelly and Rye, 1979); Dayu, China (Tanelli, 1982; Elliott, 1992); Dajishan, China (Elliott, 1992); Cornwall, United Kingdom (Hosking, 1969); Herberton, Australia (Blake, 1972); Lost River, Alaska, United States (Sainsbury, 1964; Dobson, 1982); Erzgebirge, Czechoslovakia (Janecka and Stempok, 1967); Baid al Jimalah and Silsilah, Saudi Arabia (du Bray and others, 1988; Kamilli and others, 1993).

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include tin skarn (Model 14b), tungsten skarn (Model 14a), tin replacement deposits (Model 14c), complex tin-silver-sulfide veins, Climax-type molybdenum deposits (Model 16), and molybdenum vein and greisen deposits (Model 16a, Kotlyar and others, 1995).

Potential environmental considerations

Both tin and tungsten are rare metals and have low abundances in the earth's crust. Consequently, the quantities of these metals that are mined are much smaller than other metals like copper, lead, and zinc. In addition, the United States is largely reliant on imports rather than domestic production. For example, in 1993, 81 percent of tin and 84 percent of tungsten consumed in the United States was imported (U.S. Bureau of Mines, 1994).

Potential for significant geoenvironmental impact is minor. Scarce data are available but the environmental impact is generally dependent on the sulfide mineral content of tungsten and tin ore. The principal ore minerals; wolframite series, scheelite, and cassiterite; are moderately to highly resistant to physical and chemical weathering and tend to concentrate in eluvial or alluvial deposits. The mobility of tin in natural environments is low (Rose and others, 1979). Cassiterite, the principal tin ore mineral, is highly resistant to both chemical and physical weathering and can be transported long distances from source areas to be concentrated in stream, beach, or marine placers. The mobility of tungsten is intermediate to low in neutral pH water (Rose and others, 1979) but tungsten concentrations in alkaline water, including some hot springs and saline lakes (Krauskopf, 1969), may be elevated. Extraordinary concentrations of 40-64 mg/l tungsten have been reported for brines of Searles Lake, Calif.; hot springs feeding Searles Lake contain as much as 240 µg/l tungsten (Carpenter and Garrett, 1959). The principal ore minerals, wolframite and scheelite, are similar to cassiterite in resistance to chemical weathering but are somewhat less resistant than cassiterite to physical weathering. Tungsten ore minerals are brittle and readily break down into fine particles that disperse into fine-grained sediment. Therefore, tungsten placers are found only near lode sources.

The sulfide mineral content of tin and tungsten ore is generally low and seldom exceeds a few percent. In this ore, the principal sulfide minerals that have significant acid-generating capacity are pyrite, chalcopyrite, and arsenopyrite. Host rock and ore may be enriched in molybdenum, thorium, and uranium; these elements may be

mobilized in highly acid environments.

The majority of deposits are in terrane consisting of plutonic granitic rocks and pre-intrusive clastic sedimentary or metasedimentary rocks that have low acid buffering capacity. A potential hazard in regions containing these types of deposits is the presence of high abundances of radon inside buildings because most of these deposits are hosted by rock with elevated uranium abundances. For example, in the United Kingdom, the highest abundances of radon are found in the counties of Cornwall and Devon (Scivyer and others, 1993), a region long famous for production of tin and tungsten from lode deposits associated with granitic plutons (Hosking, 1969). Radon is a health hazard in some underground Cornish mines (Dungey and others, 1979).

Mining, milling, and smelting have low to moderate environmental impact. Milling generally involves gravity, flotation, and magnetic separation; reagents used are generally benign. Concentrates are of high unit value and can be shipped long distances to processing plants and smelters. Smelters are not particularly harmful but may release sulfur dioxide.

Exploration geophysics

Magnetic, gravity, and radiometric surveys can be used to define areas in which prospective leucocratic granites may be present (Hoover and others, 1992). These granites tend to be associated with gravity and magnetic lows and have elevated radioelement (uranium, thorium, and potassium) abundances. Airborne radiometric surveys may identify exposed parts of prospective plutons. Remote sensing techniques may help define exposed leucocratic granites or detect altered areas. At the district or deposit scale and in the less common case of high sulfide ore, audio magnetotelluric techniques, induced polarization, and electric-field-ratio profiling can be used to map variations in rock resistivity due to sulfide mineral content.

References

Hosking (1969), Kelly and Rye (1979), Cox and Bagby (1986), Reed (1986a,b), du Bray and others (1988), and Elliott (1992).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

The most common tungsten vein deposits are quartz-wolframite veins. These range from less than 0.1 to about 10 million metric tonnes of ore containing 0.4 to 1.6 percent WO_3 ; median size and grade is 680,000 metric tonnes and 0.81 percent WO_3 (Menzie and others, 1992). Tin vein deposits range from less than 0.01 to about 10 million metric tons of ore containing 0.5 to 2.5 percent tin; median size and grade is 240,000 metric tonnes and 1.3 percent tin (Menzie and Reed, 1986a). Tin greisen deposits are generally larger than tin or tungsten vein deposits and range from about 0.8 to 70 million metric tons containing 0.2 to 0.5 percent tin; median size and grade is 7.2 million metric tonnes and 0.28 percent tin (Menzie and Reed, 1986b).

Although the size of individual deposits may be small to moderate, the tendency of these deposits to cluster can profoundly affect the environment, economy, and culture of a region, as in Cornwall, U.K.; Dayu district, Jiangxi Province, China; and the Erzgebirge, Czechoslovakia and Germany.

Host rocks

Tin and tungsten deposits exhibit a close spatial association with granitic plutonic rocks, especially late-stage, highly evolved, specialized biotite and (or) muscovite (S-type or A-type) granites and leucogranites. Small to moderate-sized cupolas of larger subsurface plutons are especially favorable hosts; deposits may be endo- or exocontact. Exocontact deposits usually are in pelitic and arenaceous sedimentary or metamorphic rocks and within the contact metamorphic aureole of a pluton. Most endocontact deposits, including tin greisens, and many tin and tungsten veins, are in or near cupolas and ridges developed on the roof or along margins of granitoids.

Surrounding geologic terrane

Surrounding terrane is variable but generally dominated by felsic plutonic rocks and sequences of pelitic/arenaceous sedimentary or metamorphic rocks. Regions with tin and tungsten deposits, such as southeastern China, commonly have a geologic history of multiple orogenic and tectonic events. Genesis of highly-evolved specialized granites associated with tin-tungsten deposits often involves several stages of magmatism. Regional structures may localize emplacement of favorable granitoids, whereas local structures, including faults and breccia zones, may localize ore deposition.

Wall-rock alteration

Alteration directly associated with ore includes greisenization, albitization, and (or) tourmalinization. Greisen is a type of phyllic alteration (including sericitic) characterized by Li-F-bearing micas, topaz, tourmaline, fluorite, and quartz. Kaolinization, a type of argillic alteration, is widespread in parts of Cornwall, U.K. Silicification is also important, especially in the contact aureoles of granitic plutons and cupolas. Other alteration types include microclinization, chloritization, and hematization. Zoned alteration has been identified in some tungsten vein systems, including the Xihuashan mine, Dayu district, China, where upper parts of veins have well developed greisen zones; middle parts have quartz-rich greisen and silicification; and lower parts have K-feldspar-rich greisen. Higher tungsten grades are found in the upper and middle portions of veins (Wu and Mei, 1982).

Most alteration assemblages associated with tin and tungsten vein and greisen deposits have low acid buffering capacity. Zones of chloritic or feldspathic alteration, usually minor in extent, have low to moderate acid buffering capacity.

Nature of ore

Most vein deposits consist of individual veins or sets of veins that are individually minable. Some mines and districts contain hundreds of such veins. The mineralized zone at the Xihuashan mine in the Dayu district, China, consists of more than 650 veins arranged in three sets of steeply dipping parallel veins (Elliott, 1992). The veins have an average thickness of 0.4 m (maximum of 3.6 m), average length of 150 m (maximum of 1,075 m), and vertical extent of about 250 m. Other deposits consist of bulk-minable vein stockworks, as do some parts of the tungsten deposit at Baid al Jimalah in Saudi Arabia (Kamilli and others, 1993) and the Hemerdon deposit in U.K. (Mining Magazine, 1979). Some are truly disseminated in greisenized granite cupolas, such as Silsilah tin deposit in Saudi Arabia (du Bray and others, 1988). Less commonly, tin greisens may have the form of pipes, lenses, or irregular breccia zones.

Deposit trace element geochemistry

Most tin and tungsten vein and greisen deposits have a close spatial association with highly evolved peraluminous, S-type, A-type, ilmenite series, or metallogenically specialized granitic rocks. These granites have high contents of specific rare elements (F, Rb, Li, Sn, Be, W, and Mo) relative to normal granites. They may also have elevated concentrations of B, Nb, Ta, U, Th, and REE. Mineralized veins and greisens are usually extremely enriched in lithium, fluorine, rubidium, boron, and beryllium and also contain sulfide and sulfosalt minerals of Cu, Pb, Zn, Bi, Ag, As, and Sb. Their sulfur and heavy metal contents, however, are usually small.

Ore and gangue mineralogy and zonation

Minerals listed in decreasing order of abundance; potentially acid-generating minerals underlined.

Tungsten: Vein mineralogy varies from simple, consisting almost entirely of quartz and wolframite, to complex as at Pasto Bueno, Peru, and Panasqueira, Portugal. At Pasto Bueno, the principal vein minerals are wolframite, tetrahedrite-tennantite, sphalerite, galena, and pyrite in a gangue of quartz, fluorite, sericite, and carbonate. Minor amounts of molybdenite, chalcopyrite, bornite, arsenopyrite, enargite, stolzite, scheelite, zinnwaldite, topaz, tungstite, and native arsenic are present (Landis and Rye, 1974). At Panasqueira, more than 50 vein-forming minerals, including sulfide, sulfosalt, oxide, carbonate, silicate, phosphate, and tungstate minerals, have been identified (Kelly and Rye, 1979). In general, the most common minerals in tungsten vein deposits in addition to quartz are: wolframite, molybdenite, bismuthinite, pyrite, pyrrhotite, arsenopyrite, bornite, chalcopyrite, scheelite, cassiterite, beryl, mica, and fluorite.

Studies of zoning and paragenesis in many tungsten vein deposits (Landis and Rye, 1974; Kelly and Rye, 1979; Wu and Mei, 1982) indicate that, in general, tungsten minerals form earlier, at higher temperatures, and possibly closer to an igneous source than sulfide and carbonate minerals. A general mineral precipitation sequence from silicate to oxide, sulfide, and finally carbonate minerals is common to many deposits.

Tin: The mineralogy of tin vein deposits is extremely varied and complex, especially where sulfide and sulfosalt minerals are present. The most common minerals are cassiterite, wolframite, arsenopyrite, molybdenite, hematite, scheelite, beryl, galena, chalcopyrite, sphalerite, stannite, and bismuthinite in addition to ubiquitous quartz.

The Cornwall region (U.K.) is frequently cited as one of the classic areas of ore zoning, with Sn, Cu, Pb-Zn, Fe-(Mn, Sb) zones distributed sequentially around individual intrusive centers and arranged according to depth to granite contacts. The zones are roughly parallel to granite-metasediment contacts and may represent paleoisogeothermal surfaces (Guilbert and Park, 1986). The tin zone, the deepest zone, is generally found from depths of about

1,300 m within the granite to a short distance outside the granite contacts in metasedimentary rocks (Guilbert and Park, 1986).

In most greisen deposits, polyphase mineralization and multiple mineralizing centers control ore distribution and render identification of zoning patterns quite difficult. Nevertheless, the idealized disseminated greisen deposit associated with an individual cupola is zoned with respect to distributions of Sn, Mo, As, Bi, W, Be, Ag, Pb, and Zn (Hosking, 1969; Reed, 1986b). Abundances of elements toward the beginning of this list are greatest in hydrothermally altered rocks nearest mineralized cupolas, whereas abundances of elements toward the end of the list are greatest in distal parts of mineralized areas. Alteration zoning consists of albitization below the ore; pervasive greisenization with quartz-muscovite-topaz \pm fluorite \pm tourmaline; and chloritic alteration. Pyrite and arsenopyrite are common in the strongly greisenized zones. In addition to cassiterite and wolframite, other minerals include molybdenite, bismuthinite, native bismuth, pyrrhotite, bornite, chalcopyrite, scheelite, beryl, tetrahedrite-tennantite, sphalerite, galena, enargite, hematite, stannite, sulphostannates, siderite, and calcite. Complex uranium, thorium, rare earth element oxide and phosphate minerals are commonly present in minor amounts.

Mineral characteristics

Tin-tungsten veins are commonly coarse-grained; grain sizes as much as several cm are common and, in the Dajishan mine, China, wolframite crystals up to 1 m in length are found in quartz veins (Elliott, 1992). Very large wolframite crystals are also present at deposits in eastern Nevada. Ore and gangue minerals in tin greisens are finer-grained. Quartz is the most common gangue mineral in both veins and greisen and may account for 90 percent or more of vein fillings. Ore and gangue minerals other than quartz are commonly enclosed or capsulated by quartz thus protecting them from oxidation and weathering by surface and ground water. Post-mineralization faults, however, may expose ore and gangue, including sulfide minerals, to oxidation and solution in mine water.

Secondary mineralogy

Secondary tin and tungsten minerals are rare and, if present, have limited geoenvironmental impact. Varlamoffite ((Sn,Fe)(O,OH)₂), a complex oxidation product of stannite, has been reported from numerous localities. The oxidation and weathering of wolframite or scheelite deposits can produce small amounts of tungstite (WO₃·H₂O) and (or) ferritungstite ((W,Fe)(O,OH)₃). Where the sulfide and (or) sulfosalt mineral content is high oxidation and weathering may result in the formation of secondary and supergene minerals, some of which, including goethite, limonite, jarosite, chalcantinite, and others, are soluble (underlined).

Topography, physiography

Tin and tungsten vein and greisen deposits are found in areas of varied topography. Granitic plutonic rocks associated with these deposits tend to form positive areas of moderate to high relief. Silica-rich rocks such as greisens, stockwork vein zones, and quartz veins form knobs or linear ridges in areas of low relief.

Hydrology

Tin and tungsten veins and greisens are commonly vuggy and are zones of high permeability relative to surrounding granitic or metasedimentary rocks. In addition, post-mineralization faulting may follow veins and large, individual veins may contain major water courses, making control of mine drainage a potential problem.

Mining and milling methods

Mining: Tin and tungsten veins and greisens are mined by conventional underground and open-pit methods. Most production is probably from underground mines because of the relative small size, narrow widths, and depths of orebodies. Cut-and-fill stoping and open stoping are probably most common underground methods.

Ore dressing: Tungsten--Gravity and flotation, using organic compounds, methods are most commonly used. Xanthate collectors are used to float sulfide minerals from scheelite ore; subsequently, fatty acids and soaps are used to float scheelite. Fatty acids are also used to float wolframite. Magnetic and electrostatic methods are also used. Magnetic methods are used to separate wolframite and cassiterite. Tin--Gravity is only practical way of preparing cassiterite concentrates. Complex sulfide ore that contains a significant amount of tin in sulfide or sulfosalt minerals requires special treatment that may involve flotation.

Because of the friable nature of both tin and tungsten minerals, a significant amount of these minerals may be lost in finer grained material (slime) during milling. Care must be exercised in the initial crushing, grinding, and first-stage separation to prevent excessive sliming.

Metallurgy: Tungsten--Tungsten concentrates, containing approximately 60-65 percent WO_3 (scheelite), can be combined with coke and steel in an electric furnace and reduced to ferrotungsten; alternatively, concentrates can be treated chemically to produce intermediate products or tungsten metal (as powder). Because of tungsten's high melting temperature ($3,400^\circ C$), chemical decomposition and purification are used, instead of pyrometallurgy, to produce tungsten metal. This process involves three steps: (1) decomposition of tungsten minerals, (2) purification of tungstic oxide, and (3) production of metal powder (Li and Wang, 1955). Most current production, trade, and consumption of tungsten, however, involves an intermediate product called ammonium paratungstate (APT). The preparation of APT is a chemical process involving calcination, pressure digestion, filtration and purification, solvent extraction, and crystallization (Lassner, 1982). Tin--Smelting tin from cassiterite concentrates generally involves either a (1) carbo-thermic process of heating tin concentrate with carbon or (2) fuming process in which tin concentrate is heated with sulfur or sulfide minerals to volatilize stannous sulfide. A chloride volatilization process is also used in tin smelting (Harris, 1979).

ENVIRONMENTAL SIGNATURES

Drainage signatures

Because of the low solubility of tin and tungsten minerals, high values in water are not expected. In the unusual case, in which the primary ore sulfide mineral content is high, highly acidic water with elevated abundances of iron, aluminum, fluorine, and variable copper and zinc may characterize drainage from mines or mine wastes. Highly acid water can also mobilize fluorine and uranium, whose abundances are commonly elevated in tin and tungsten ore.

Metal mobility from solid mine wastes

In general, metal mobilities from solid mine wastes are low. When the sulfide and (or) sulfosalt mineral content of ore is moderate to high, metal mobilities increase due to production of low pH water and formation of soluble secondary minerals.

Soil, sediment signatures prior to mining

Soil and stream sediment may have elevated tin and tungsten contents (tens to hundreds of ppm) and may contain anomalous abundances of elements characteristic of specialized granites (F, Rb, Be, Nb, Ta, Mo, U, Th, Li, and REE). Other possible pathfinder elements are As, Bi, B, Cu, Pb, and Zn.

Potential environmental concerns associated with mineral processing

Potential hazards include:

- (1) High silica dust blowing from unstable mill tailings.
- (2) Possible high concentrations of U, Th, Be, Mo, As, P, and REE in mill tailings and smelter waste due to primary enrichments of these elements in host rock and ore and the gravity and magnetic separation methods used in milling, which concentrate high specific gravity minerals.
- (3) Waste from APT process includes alkaline effluents and residues containing Mo, P, As, U, Th, and REE (Raddatz and others, 1988).

Smelter signatures

Tin smelters may release sulfur dioxide and other volatile elements, including arsenic, fluorine, chlorine, and others, present in ore or used in smelting process.

Climate effects on environmental signatures

The effects of various climatic regimes on the geoenvironmental signature specific these deposits are not known. However, in most cases the intensity of environmental impact associated with sulfide-bearing mineral deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell.

Geoenvironmental geophysics

Audio magnetotelluric techniques, induced polarization, and electric-field-ratio profiling can be used to detect hydrothermally altered areas and the presence of ground water. Gamma ray spectroscopy can be used to measure uranium and thorium abundances and radon can be determined by several special collectors used in conjunction with laboratory analysis.

REFERENCES CITED

- Blake, D.H., 1972, Regional and economic geology of the Herberton-Mount Garnet area, Herberton tinfield, North Queensland: Australia Bureau of Mineral Resources Bulletin 124, 265 p.
- Carpenter, L.C., and Garrett, D.E., 1959, Tungsten in Searles Lake: *Mining Engineering*, v. 11, p. 301-303.
- Cox, D.P., and Bagby, W.C., 1986, Descriptive model of W veins, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 64.
- Cox, D.P., and Singer, D.A., 1986, *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, 379 p.
- Dobson, D.C., 1982, Geology and alteration of the Lost River tin-tungsten-fluorine deposit, Alaska: *Economic Geology*, v. 77, p. 1033-1052.
- du Bray, E.A., Elliott, J.E., and Stuckless, J.S., 1988, Proterozoic peraluminous granites and associated Sn-W deposits, Kingdom of Saudi Arabia, *in* Taylor, R.P., and Strong, D.F., eds., *Recent advances in the geology of granite-related mineral deposits: Canadian Institute of Mining and Metallurgy, special volume 39*, p. 142-156.
- Dungey, C.J., Hore, J., and Waller, M.D., 1979, An investigation into control of radon and its daughter products in some Cornish mine atmospheres: *Transactions of the Institute of Mining and Metallurgy*, v. 88, p. A35-A43.
- Elliott, J.E., 1992, Tungsten- geology and resources of deposits in southeastern China, *in* DeYoung, J.H., Jr., and Hammarstrom, J.M., eds., *Contributions to commodity geology research: U.S. Geological Survey Bulletin 1877*, p. 11-110.
- Guilbert, J.M., and Park, C.F., Jr., 1986, *The geology of ore deposits: W.H. Freeman and Co., New York*, 985 p.
- Harris, J.H., 1979, The problems of tin, *in* Lead, Zinc, Tin '80: The Metallurgical Society of AIME, Warrendale, PA., p. 733-753.
- Hoover, D.B., Heran, W.D., and Hill, P.L., 1992, The geophysical expression of selected mineral deposit models: *U.S. Geological Survey Open-File Report 92-557*, 129 p.
- Hosking, K.F.G., 1969, The nature of primary tin ores of the south-west of England, *in* A Second Technical Conference on Tin: Bangkok, International Tin Council, v. 1, p. 21-83.
- Janecka, J., and Stempok, M., 1967, Endogenous tin mineralization in the Bohemian massif, *in* A Technical Conference on Tin: London, International Tin Council, v. 1, p. 245-266.
- Kamilli, R.J., Cole, J.C., Elliott, J.E., and Criss, R.E., 1993, Geology and genesis of the Baid al Jimalah tungsten deposit, Kingdom of Saudi Arabia: *Economic Geology*, v. 88, no. 7, p. 1743-1767.
- Kelly, W.C., and Rye, R.O., 1979, Geologic, fluid inclusion, and stable isotope studies of the tin-tungsten deposits of Panasqueira, Portugal: *Economic Geology*, v. 74, p. 1721-1822.
- Kotlyar, B.B., Ludington, Steve, and Mosier, D.L., 1995, Descriptive, grade, and tonnage models for molybdenum-tungsten greisen deposits: *U.S. Geological Survey, Open-File Report 95-584*, 30 p.
- Krauskopf, K.B., 1969, Tungsten (Wolfram), *in* Handbook of Geochemistry, Springer-Verlag, v. II/2, p. 74-B to 74-O.
- Landis, G.P., and Rye, R.O., 1974, Geologic, fluid inclusion, and stable isotope studies of the Pasto Bueno tungsten-base metal ore deposit, northern Peru: *Economic Geology*, v. 69, p. 1025-1059.
- Lassner, Erik, 1982, Modern methods of APT processing, *in* Tungsten; 1982, Proceedings of the Second International Tungsten Symposium, June 1982: Mining Journal Books, Ltd., p. 71-80.
- Li, K.C., and Wang, C.Y., 1955, *Tungsten: Reinhold, New York*, 506 p.
- Menzie, W.D., Jones, G.M., and Elliott, J.E., 1992, Tungsten- grades and tonnages of some deposits, *in* DeYoung, J.H., Jr., and Hammarstrom, J.M., eds., *Contributions to commodity geology research: U.S. Geological Survey Bulletin 1877*, p. J1-J7.
- Menzie W.D., and Reed, B.L., 1986a, Grade and tonnage model of Sn veins, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 67-69.
- _____ 1986b, Grade and tonnage model of greisen Sn deposits, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 71-72.
- Mining Magazine, 1979, Hemerdon- Britain's largest tungsten deposit: *Mining Magazine*, October, p. 342-351.

- Raddatz, A.E., Gomes, J.M., and Carnahan, T.G., 1988, Preparation of ammonium paratungstate from a sodium tungstate-sodium chloride phase: U.S Bureau of Mines, Report of Investigations 9165, 10 p.
- Reed, B.L., 1986a, Descriptive model of Sn veins, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 67.
- _____ 1986b, Descriptive model of Sn greisen deposits, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 70.
- Rose, A.W., Hawkes, H.E., and Webb, J.S., 1979, Geochemistry in mineral exploration: Academic Press, 657 p.
- Sainsbury, C.L., 1964, Geology of the Lost River mine area, Alaska: U.S. Geological Survey Bulletin 1287, 101 p.
- Scivyer, Chris, Woolliscroft, Michael, and Parkins, Lynn, 1993, The development and implementation of radon protective measures in UK dwellings, *in* The 1993 International Radon Conference, supp. #2: The American Association of Radon Scientists and Technologists, September, 1993, Denver, Colo., 5 p.
- Tanelli, G., 1982, Geological setting, mineralogy and genesis of tungsten mineralization in Dayu district, Jiangxi (People's Republic of China), an outline: *Mineralium Deposita*, v. 17, no. 2, 279-294.
- U.S. Bureau of Mines, 1994, Mineral Commodity Summaries 1994, 201 p.
- Wu Yongle and Mei Yong Wen, 1982, Multi-phase intrusion and multi-phase mineralization in Xihuashan tungsten ore field, *in* Hepworth, J.V., and Yu Hong Zhang, eds., Tungsten geology, Jiangxi, China: Bandung, Indonesia, ESCAP/RMRDC, p. 437-449.

CLIMAX MO DEPOSITS (MODEL 16; Ludington, 1986)

by Steve Ludington, Arthur A. Bookstrom, Robert J. Kamilli, Bruce M. Walker, and Douglas P. Klein

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Deposits are large (100 to 1,000 million metric tons of ore containing 0.06 to about 1 weight percent molybdenum) and consist of stockworks of molybdenite-bearing veins and veinlets, within larger masses of hydrothermally-altered rock. Orebodies are in and above the apices and on the apical flanks of small metaluminous porphyry stocks of the high-silica (>75 weight percent SiO₂) rhyolite-alkalic suite of Carten and others (1993). Orebodies mimic the shape of and surround the top of their subjacent stocks. Multiple intrusions and overlapping ore shells are characteristic of productive systems; at Henderson, Colo., at least eleven intrusions are associated with mineralization processes. Individual ore shells, which coincide with orthoclase-bearing zones of altered rock, are commonly underlain by highly silicified rock and (or) by characteristic zones of layered unidirectional solidification features (USTs) or *stockscheider*; these zones consist of crenulate layers of quartz + fluorite or other minerals that are separated by layers of aplite and aplite porphyry. These layers parallel contacts between stocks; crystals terminate inward from these contacts.

Climax molybdenum deposits exhibit distinctive zoned alteration patterns. Early silicic alteration, along with surrounding potassic alteration (K-feldspar replaces plagioclase) of porphyry and wall rock characterize the inner zone. Above each ore shell is a much larger, lower temperature, phyllic zone, that consists of stockworks of veinlets that contain quartz, pyrite, and (or) sericite, and (or) illite, and (or) topaz, with phyllic envelopes, some of which may contain tungsten (wolframite) and tin (cassiterite). The entire molybdenum system commonly is surrounded by a very large zone of propylitic alteration, in which iron- and magnesium-bearing minerals are converted to various combinations of chlorite, albite, calcite, and epidote. At Silver Creek (Rico), Colo., this zone extends nearly 2 km above the molybdenum deposit (Larson and others, 1994). Shale-hosted deposits may be surrounded by a large zone of biotite hornfels. All alteration assemblages display anomalously high amounts of fluorine, which is contained in fluorite, topaz, and micas; the deposits share many characteristics with greisens.

Examples

Climax (Wallace and others, 1968), Henderson (Carten and others, 1988), Urad, Mount Emmons, Winfield, Middle Mountain, Silver Creek (Rico), and Redwell Basin, all in Colo.; Questa, N. Mex.; Pine Grove, Utah (Keith and others, 1986); Mount Hope, Nev. (Westra and Riedell, 1995).

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include minor, silver-rich, polymetallic vein (Models 22c) and polymetallic replacement deposits (Models 19a) that appear to be concentric and distal to some deposits. Veins commonly contain quartz, fluorite, rhodocrosite, base-metal sulfide minerals, and tetrahedrite. These base-metal systems may be more extensive in some environments, as at Silver Creek (Rico) (Larson, 1987), and Crested Butte (Sharp, 1978).

Climax deposits, possibly underlain by molybdenum greisen deposits (Kotlyar and others, 1995), are genetically related to molybdenum, tin, and tungsten greisen systems. Burt and others (1982) have suggested that rhyolite-hosted tin deposits may also be underlain by Climax type deposits.

Potential environmental considerations

Oxidation of pyrite in large, unmined deposits, such as Winfield, Colo. (Ranta, 1974), may contribute significant acidic drainage to nearby streams. Mining and milling of large tonnages of sulfide-mineral-bearing stockwork ore may exacerbate acid drainage problems, although most pyrite is outside orebodies. Tailings may contain finely-ground pyrite-bearing rock that, when oxidized, may generate large quantities of acid. This acid, if not artificially neutralized, may be partially neutralized as streams traverse plagioclase- or carbonate mineral-bearing bedrock. Most other minerals and elements present in these deposits are relatively non-toxic.

Molybdenite differs from most sulfide minerals in that it releases molybdenum as an anion, not a cation, during weathering. Geochemical mobility of most metallic cations increases with acidity, whereas mobility of molybdate anions increases with alkalinity. The molybdate ion, which is stable at low pH, is geochemically

immobile, because it is strongly coprecipitated with and (or) adsorbed on ferric oxyhydroxide at low pH. Plants growing in soil with a pH of 5.5 or less commonly contain only trace amounts of molybdenum, whereas plants growing in soil with a pH of 6.5 or higher are commonly enriched in molybdenum (Hansuld, 1966).

Molybdenosis is a disease that affects ruminants that graze on molybdenum-rich vegetation that grows on alkaline soil in which the ratio of bioavailable copper to bioavailable molybdenum (as molybdate) is less than 2:1. Thus, molybdenosis is more related to climatic factors, soil alkalinity, and the relative bioavailability of copper and molybdenum, than to point sources of molybdenum.

High fluorine concentrations associated with Climax deposits may be beneficial. Children who grew up at Climax, Colo., had brown-speckled, but cavity-free teeth, due to the high fluoride content of local drinking water.

Uranium concentrations are anomalously high in Climax molybdenum systems. Granitic rocks associated with the deposits contain uranium-bearing accessory minerals, most of which are not recovered but deposited with mill tailings; uranium abundances in Ten Mile Creek, which receives input from Climax tailings ponds, are significantly elevated, however. Distal veins peripheral to Climax deposits, commonly several kilometers distant, may also have anomalously high uranium contents. Thus, radon gas in the mines is a potential hazard; radon abundances must be monitored and mitigated by proper ventilation, as necessary.

Exploration geophysics

Alteration associated with shallow or exposed deposits produce diagnostic color (reflectance) patterns on remote-sensing images. Pyrite and hydrothermal clays in the phyllic alteration zone display reduced resistivity and high induced potential anomalies (Fritz, 1979). Anomalous uranium, thorium, and potassium abundances can be mapped with airborne gamma-ray spectrometry. Radon in mines or associated with mine-related ground water can be identified using simple detectors. At Mt. Emmons, a magnetic anomaly is coincident with a layer of hydrothermal magnetite below the molybdenite zone (Fritz, 1979; Thomas and Galey, 1982). Local gravity is variable as a function of rock types present in the shallow subsurface; regional gravity lows, produced by multistage, high-silica plutons and underlying granitic batholiths are nearly ubiquitous in association with these deposits. Self potential lows have been reported over phyllic (quartz-sericite-pyrite) alteration zones associated with several deposits (Corry, 1985).

References

Wallace and others (1968), White and others (1981), Carten and others (1988), and Keith and others (1986).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Most deposits are >100 million metric tons, and they may be as large as 1 billion metric tons. Such large deposits may result in special waste storage problems that may impact local geography and stream courses. Hydrothermal alteration may affect an area of many square kilometers, although orebody horizontal cross-sectional areas are usually less than one kilometer.

Host rocks

Deposits are found in crystalline, volcanic, and sedimentary rocks of diverse ages in the western United States.

Surrounding geologic terrane

Surrounding terrane is not diagnostic nor particularly significant with regard to potential environmental impact. Many of these deposits are found in young mountain ranges where mining operations may conflict with scenic and recreational values. Deposits located at high elevations, in the headwaters of drainages, can impact large downstream areas.

Wall-rock alteration

Wall-rock alteration includes (1) high temperature assemblages: quartz + fluorite ± molybdenite, quartz + K-feldspar + fluorite ± molybdenite, and quartz alone, all found near the center of the hydrothermal system; (2) moderate temperature assemblages: quartz + K-feldspar + magnetite + brown biotite ± topaz ± fluorite, and quartz + sericite + green biotite ± topaz ± fluorite; and (3) low temperature assemblages: pyrite + sphalerite + garnet + rhodocrosite + clay, and a large propylitic zone (albite + epidote + chlorite) that may extend kilometers beyond intrusive centers. Pyrite, a constituent of moderate- and low-temperature assemblages, is the most significant mineral with regard to environmental concerns. Rocks from the quartz-sericite-pyrite zone at Climax, Colo., contain about 2 to 10 volume percent (4 to 20 weight percent) pyrite.

Nature of ore

Ore bodies are typically overlapping, inverted, and saucer-shaped, and are stacked above one another, with or without offset. High grade parts of composite ore bodies form where individual ore bodies associated with discrete stocks overlap. Assay walls of ore bodies are typically quite sharp.

Molybdenite is present primarily with high-temperature alteration assemblages, both as a vein-filling phase and as replacements in vein selvages. Pyrite is rarely present with molybdenite, but rather is found in later, lower-temperature veins and assemblages that cut earlier molybdenite veins. Late, insignificant sphalerite- and galena-bearing veins may cut pyrite veins in distal parts of systems.

Climax molybdenum deposits are relatively barren of other metals, except tin and tungsten, each of which may form weakly enriched zones in the outer parts or outside molybdenite ore bodies. Wolframite was recovered for many years as a by-product of mining at Climax, Colo. Tin is present primarily as cassiterite at Climax, but is in ilmenorutile at Henderson, Colo.

Deposit trace element geochemistry

Source plutons have elevated incompatible element abundances, including 200 to >1,000 ppm rubidium, 1 to >30? ppm cesium, as much as 10 ppm beryllium, 10 to >100 ppm lithium, 25 to >200 ppm niobium, 2 to >20 ppm tantalum, and 0.1 to >1 percent fluorine; most have depleted compatible element abundances, including <100 ppm zirconium, <200 ppm barium, and <100 ppm strontium. Ore-related veins and veinlets contain elevated abundances of other metals, including 4 to >100 ppm uranium, 10 to >50 ppm thorium, 10 to >200 ppm tin, and 2 to >100 ppm tungsten.

Ore and gangue mineralogy and zonation

Primary accessory minerals in ore-related intrusions at Climax, Colo., are zircon, fluorite, topaz, monazite, rutile, brannerite, hematite, and magnetite; mill concentrates also contain ilmenorutile, columbite, uraninite, metamict uranium oxide minerals, xenotime, and euxenite. In addition, ore related intrusions at Henderson, Colo., contain accessory metamict niobium oxide minerals, uranium-bearing thorite, fluocerite, apatite, and aeschynite (White and others, 1981).

Mineral characteristics

Molybdenite grain size varies widely, from about 0.2 mm in replacement veins to >10 cm in open-space filling. Pyrite is typically fine-grained and is present in alteration selvages.

Secondary mineralogy

In exposed deposits, most pyrite weathers to limonite and other iron oxide minerals, and molybdenite may alter to ferrimolybdate and (or) ilsemannite, $\text{Mo}_3\text{O}_8 \cdot n\text{H}_2\text{O}$; other secondary minerals include jarosite and various clay minerals. In wet areas, some pyrite is totally oxidized causing iron to be dissolved in drainage water; iron subsequently precipitates as hydrous iron oxide.

Where pyrite and molybdenite weather together, weathering products depend on pH, and on the ratio of iron hydroxide to acid molybdate in water draining the area. Ferrimolybdate forms in strongly acidic environments (Hansuld, 1966), molybdenum-bearing jarosite probably forms in moderately acidic environments, molybdenum-bearing iron hydroxide minerals form in weakly acidic to mildly alkaline environments, and geochemically mobile molybdate ion forms in alkaline environments, where $\text{pH} > 6$. Ilsemannite is rare and ephemeral, because conditions for its stability are rarely encountered in the normal weathering environment (Hansuld, 1966).

Weathered deposits commonly exhibit red hematite, yellow jarosite and ferrimolybdate, brown goethite, and peripheral black manganese oxide minerals.

Topography, physiography

Ore bodies are high in silica, and may be resistant, but most known deposits are deeply buried. Many known deposits are within or beneath peaks stained a distinctive red color by iron oxide minerals.

Hydrology

Annually variable runoff from winter snowmelt may dramatically affect influx into tailings ponds. Most host rocks have low porosity, but the deposits exhibit high fracture permeability.

Mining and milling methods

These deposits are large, bulk tonnage deposits, and are typically mined by open stope, block caving, and open-pit methods which typically further fracture the rocks, increasing permeability and exposing the deposit and surrounding pyritic rocks to increased flow of oxidizing ground water. Molybdenite is typically concentrated on-site by flotation of finely-ground ore.

ENVIRONMENTAL SIGNATURES

Drainage signatures

A limited amount of information is available for deposits in Colorado. Water draining pyrite-molybdenite zones has a pH of 1 to 3 and contains elevated dissolved metal abundances, including hundreds to thousands of mg/l iron and aluminum, hundreds of mg/l fluoride, tens of mg/l zinc and copper, and 1 to 10 mg/l uranium. Water draining intermediate pyrite shells has a pH of 2 to 5 and contains elevated dissolved metal abundances, including hundreds of mg/l iron and aluminum and <1 to about 10 mg/l zinc and copper. Water draining peripheral base-metal-bearing zones has a pH of about 5.5 and contains elevated dissolved metal abundances, including 1 to 200 mg/l zinc and hundreds of $\mu\text{g/l}$ to several mg/l iron and copper (Plumlee and others, 1995).

Metal mobility from solid mine wastes

Because a significant part of the molybdenite is marketed for use as a lubricant, most ore must be ground very finely in order to liberate resistant phases such as quartz and minor amounts of pyrite. When not below the water table in tailings ponds, this very fine pyrite can oxidize rapidly. Acidic drainage that percolates through and seeps from the toes of tailings is typically collected and recycled to tailings ponds, rather than being released to the environment. Waste dumps may contain several percent pyrite. Post-treatment release of water from tailings ponds can result in large abundances of uranium and fluorine in solution.

Soil, sediment signatures prior to mining

Studies of the region surrounding Henderson, Colo. (Theobald and Thompson, 1959), identified significant concentrations of wolframite, scheelite, and molybdenite in heavy-mineral concentrates from streams that drain the deposit area; metal contents of stream sediment derived from outcrops of the Urad deposit include as much as 3,000 ppm tungsten, 700 ppm molybdenum, 500 ppm tin, 3,000 ppm lead, 50 ppm copper, and 1.5 ppm silver.

Potential environmental concerns associated with mineral processing

Fine-grained silica tailings may become a dust and (or) health hazard. Molybdate ion in solution is a constituent of high-pH flotation mill effluent (Le Gendre and Runnells, 1975). However, as pyrite-bearing tailings weather, pH decreases, and acid molybdate is coprecipitated with and (or) adsorbed on ferric oxyhydroxide. In dry areas, this effect may be offset by the alkalinity of surrounding soil, in which geochemically mobile molybdate ions remains stable. Fine-grained pyrite in tailings is susceptible to rapid oxidation.

Smelter signatures

The lone molybdenum smelter in the United States is in western Pennsylvania; it uses an electrolytic process.

Climate effects on environmental signatures

In areas with higher precipitation, pyrite is more rapidly oxidized but molybdate is more rapidly fixed in iron hydroxide minerals. In most cases the intensity of environmental impact associated with sulfide-bearing mineral deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell.

Geoenvironmental geophysics

Sulfide mineral concentrations can be detected by induced polarization surveys. Acid pore water can be identified by low resistivity, and usually by enhanced induced polarization, signatures. Self potential surveys may be used to identify redox centers in tailings; heat from these centers may be identified by infrared surveys or shallow thermal

probes, though numerous interference factors may complicate these investigations. Thickness and structure of tailings may be determined using shallow seismic refraction, electrical, and ground penetrating radar surveys.

REFERENCES CITED

- Burt, D.M., Sheridan, M.F., Bikun, J.G., Christiansen, E.H., Correa, B.P., Murphy, B.A., and Self, S., 1982, Topaz rhyolites—distribution, origin, and significance for exploration: *Economic Geology*, v. 77, p. 1818–1836.
- Carten, R.B., Geraghty, E.P., Walker, B.M., and Shannon, J.R., 1988, Cyclic generation of weakly and strongly mineralizing intrusions in the Henderson porphyry molybdenum deposit, Colorado—Correlation of igneous features with high-temperature hydrothermal alteration: *Economic Geology*, v. 83, p. 266–296.
- Carten, R.B., White, W.H., and Stein, H.J., 1993, High-grade granite-related molybdenum systems—classification and origin, in Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., and Duke, J.M., eds., *Mineral deposit modeling: Geological Association of Canada Special Paper 40*, p. 521–554.
- Corry, C.E., 1985, Spontaneous polarization associated with porphyry sulfide mineralization: *Geophysics*, v. 50, no.6, p. 1985.
- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- Fritz, F.P., 1979, The geophysical signature of the Mt. Emmons porphyry molybdenum deposit, Gunnison Co. Colorado [abs], *Geophysics* v. 44, no. 3, p. 410.
- Hansuld, J.A., 1966, Behavior of molybdenum in secondary dispersion media—a new look at an old geochemical puzzle: *Mining Engineering*, v. 18, no. 12, p. 73.
- Keith, J.D., Shanks, W.C., III, Archibald, D.A., and Farrar, E., 1986, Volcanic and intrusive history of the Pine Grove porphyry molybdenum system, southwestern Utah: *Economic Geology*, v. 81, p. 553–577.
- Kotlyar, B.B., Ludington, Steve, and Mosier, D.L., 1995, Descriptive, grade, and tonnage models for molybdenum-tungsten greisen deposits: U.S. Geological Survey, Open-File Report 95-584, 30 p.
- Larson, P.B., 1987, Stable isotope and fluid inclusion investigations of epithermal vein and porphyry molybdenum mineralization in the Rico mining district, Colorado: *Economic Geology*, v. 82, p. 2141–2157.
- Larson, P.B., Cunningham, C.G., and Naeser, C.W., 1994, Hydrothermal alteration and mass exchange in the hornblende latite porphyry, Rico, Colorado: *Contributions to Mineralogy and Petrology*, v. 116, p. 199–215.
- LeGendre, G.R., and Runnells, D.D., 1975, Removal of dissolved molybdenum from wastewaters by precipitates of ferric iron: *Environmental Science and Technology*, v. 9, p. 744.
- Ludington, S.D., 1986, Descriptive model of Climax Mo deposits, in Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 73.
- Plumlee, G.S., Streufert, R.K., Smith, K.S., Smith, S.M., Wallace, A.R., Toth, Margo, Nash, J.T., Robinson, Rob, Ficklin, W.H., and Lee, G.K., 1995, Geology-based map of potential metal-mine drainage hazards in Colorado: U.S. Geological Survey Open-File Report 95-26, scale 1:750,000, 9 p.
- Ranta, D.E., 1974, Geology, alteration, and mineralization of the Winfield (La Plata) district, Chaffee County, Colorado: Golden, Colorado School of Mines, Ph.D. dissertation, 261 p.
- Sharp, J.E., 1978, A molybdenum mineralized breccia pipe complex, Redwell Basin, Colorado: *Economic Geology*, v. 73, p. 369–382.
- Theobald, P.K., and Thompson, C.E., 1959, Geochemical prospecting with heavy mineral concentrates used to locate a tungsten deposit: U.S. Geological Survey Circular 411, 13 p.
- Thomas, J.A., and Galey, J.T., Jr., 1982, Exploration and geology of the Mt. Emmons molybdenite deposits, Gunnison County, Colorado: *Economic Geology*, v. 77, p. 1985-1104.
- Wallace, S.R., Muncaster, N.K., Jonson, D.C., MacKenzie, W.B., Bookstrom, A.A., and Surface, V.E., 1968, Multiple intrusion and mineralization at Climax, Colorado, in Ridge, J.D., ed., *Ore Deposits of the United States, 1933–1967, The Graton-Sales Volume: American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., New York, NY*, p. 605–640.
- Westra, Gerhard, and Riedell, K.B., 1995, Geology of the Mount Hope stockwork molybdenum deposit, Eureka County, Nevada, [abs.]: *Geology and ore deposits of the American Cordillera-A symposium, Geological Society of Nevada, U.S. Geological Survey, Sociedad Geologica de Chile*, p. A78-A79.
- White, W.H., Bookstrom, A.A., Kamilli, R.J., Ganster, M.W., Smith, R.P., Ranta, D.E., and Steininger, R.C., 1981, Character and origin of Climax-type molybdenum deposits: *Economic Geology, 75th Anniversary Volume*, p. 270–316.

PORPHYRY CU DEPOSITS (MODEL 17; Cox, 1986)

by Leslie J. Cox, Maurice A. Chaffee, Dennis P. Cox, and Douglas P. Klein

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Porphyry copper deposits contain copper, molybdenum, and gold minerals, disseminated or in a stockwork of small veinlets within a large mass of altered rock (Singer and Mosier, 1981). The host rock is commonly a pyrite-rich porphyry ranging in composition from granodiorite to tonalite, but alkalic porphyries are locally important. In the southwestern United States, where porphyry copper deposits are abundant, associated igneous rocks are mainly Mesozoic and Cenozoic. Older plutonic, volcanic, sedimentary, and metamorphic rocks intruded by these porphyries also host ore minerals; the highest grades are found in reactive rocks such as limestone, or rocks, such as diabase, which contain abundant iron-rich minerals prior to alteration. Porphyry deposits exhibit a characteristic pattern of hydrothermal alteration, which includes biotite and K-feldspar assemblages in the center and grades outward to chlorite, actinolite, and epidote assemblages. Most deposits have a late-stage alteration assemblage that contains abundant white mica, clay, and carbonate minerals.

Examples

Bingham, Utah (Lanier and others, 1978); San Manuel, Ariz. (Lowell and Guilbert, 1970); El Salvador, Chile (Gustafson and Hunt, 1975).

Spatially and (or) genetically related deposit types

Related deposit types (Cox and Singer, 1986) include porphyry copper, skarn-related (Model 18a), base-metal skarn (Model 18c), porphyry copper-gold (Model 20c), porphyry copper-molybdenum (Model 21a), polymetallic vein (Model 22c), polymetallic replacement (Model 19a), volcanic-hosted copper-arsenic-antimony (Model 22a), quartz-alunite gold (Model 25e), distal disseminated silver-gold (Model 19c; Cox, 1992), and gold-skarn deposits.

Potential environmental considerations

Visual considerations include open pits and waste dumps from open-pit mining and from subsidence areas produced by underground block caving. Tailings from milling of ore can cause release of acid mine drainage from mine and waste dumps. Mill tailings are a source of dust. Emissions from smelters, mainly SO₂, are a significant concern; many smelters are located considerable distances from deposits.

Statistical summaries (tables 1-11) show that, relative to commonly accepted crustal abundances, as many as 28 porphyry copper deposit-related elements (Ag, As, Au, B, Cd, Co, Cu, Cs, Fe, Hg, K, La, Li, Mn, Mo, Ni, Pb, Rb, S, Sb, Se, Sn, Sr, Te, Tl, U, V, W, and Zn) are locally to generally enriched in and around these deposits. Although any of these 28 elements might be deemed to be sufficiently enriched to produce potential environmental problems when dispersed into the area around a deposit, many of these enrichments are probably not important. In fact, only 10 of these elements (As, Cd, Cu, Fe, Mo, Pb, S, Sb, Te, and Zn) are likely to be present in sufficiently elevated concentrations to have associated environmental impact.

Exploration geophysics

The distribution of disseminated copper sulfide minerals and pyrite can be mapped using induced polarization; resistivity surveys may define low resistivity areas associated with altered sulfide-mineral-bearing rock (Elliot and MacLean, 1978; Pelton and Smith, 1976). Detailed magnetic surveys may also help delineate altered rock if contained magnetic minerals have been destroyed by alteration. Peripheral magnetite-bearing rocks, including magnetite-rich skarns, may produce magnetic anomaly highs around porphyry copper deposits (Grant, 1985). Regional magnetic and gravity anomalies may identify intrusions that host porphyry copper deposits; magnetic and gravity maps, as well as remote sensing images may show lineaments, associated with large faults, and clusters of intrusions that may host porphyry copper deposits (Carlson and Mabey, 1963; Raines, 1978; Turner and others, 1982; Abrams and others, 1983). Large alteration halos surrounding exposed porphyry copper deposits are easily identified on remote sensing images. Vegetation in the vicinity of buried porphyry copper deposits may be stressed by metal uptake. Remote sensing may identify buried deposits if associated stressed vegetation produces reflectance anomalies (Birnie and Francica, 1981; Knepper, 1989).

Table 1. Summary statistics for 326 samples of mostly unoxidized rocks from the hypogene zone of porphyry copper deposits, southern Arizona, with Cu \geq 1,000 ppm (Maurice Chaffee, unpub. data).

[Most concentrations in parts per million; % following an element indicates weight percent data. N, not detected at lower limit of determination, in parentheses. L, detected at concentration less than lower limit of determination, in parentheses. Mean values based on unqualified values only. Most elements determined by semiquantitative spectroscopic analysis; except, "aa" following element symbol indicates atomic-absorption analysis; "inst" indicates specific-ion electrode (F), titrimetric (S), fluorometric (U) analysis. Leaders (-) indicate no meaningful value]

Element	Range of values		Geometric mean	Number unqualified	Percent unqualified
	Minimum	Maximum			
Ag	N(0.5)	30	1.3	308	94
As-aa	N(1)	500	5.5	296	91
Au-aa	N(0.002)	1.1	0.031	325	99.6
B	N(10)	200	18	269	83
Ba	150	3,000	740	326	100
Be	L(1)	2	1.1	250	77
Bi	N(10)	500	--	16	4.9
Ca %	L(0.05)	5.0	0.51	325	99.6
Cd	N(20)	150	--	4	1.2
Co	N(5)	70	18	319	98
Cr	N(10)	300	33	275	84
Cu	1,000	20,000	2,000	326	100
Cs	N(10)	150	20	233	71
F-inst ¹	300	1,000	440	32	100
Fe %	0.7	10	4.1	326	100
Hg-aa	N(0.02)	1.1	0.04	279	86
K-aa %	0.70	8.7	2.9	326	100
La	N(20)	150	46	323	99
Li	L(1)	200	11	323	99
Mg %	0.15	3.0	0.86	326	100
Mn	50	>5,000	630	325	99.6
Mo	N(5)	2,000	20	225	69
Na-aa %	N(0.1)	3.7	0.65	288	88
Ni	N(5)	150	22	311	95
Pb	10	5,000	49	326	100
Rb	70	70	170	326	100
S-inst	0.02	15.5	1.2	326	100
Sb-aa	N(1)	600	3.2	211	65
Sc	L(5)	50	13	325	99.6
Sn	N(10)	70	--	34	10
Sr	N(100)	1,000	260	286	88
Te-aa	N(0.01)	6,000	0.20	322	99
Ti %	0.10	1.0	0.41	326	100
Tl-aa	0.30	56	1.2	326	100
U-inst	0.14	30	1.2	326	100
V	20	700	110	326	100
W	N(50)	150	--	17	5.2
Y	N(10)	70	19	322	99
Zn-aa	5	17,000	130	326	100
Zr	30	500	140	326	100

¹Fluorine determined in only 32 samples.

References

Lowell and Guilbert (1970), Gustafson and Hunt (1975), Lanier and others (1978), and Titley, (1982).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Tonnage estimates for the 90th, 50th, and 10th percentiles are respectively 19, 140, and 1,100 million metric tons (Singer and others, 1986).

Host rocks

Host rocks include tonalite to monzogranite or syenitic porphyry and associated breccia pipes intruding granitic,

Table 2. Summary statistics for 247 samples of mostly unoxidized rocks from the hypogene zone of porphyry copper deposits, southern Arizona, with Cu <1,000 ppm (Maurice Chaffee, unpub. data).

[Most concentrations in parts per million; % following an element indicates weight percent data. N, not detected at lower limit of determination, in parentheses. L, detected at concentration less than lower limit of determination, in parentheses. Mean values based on unqualified values only. Most elements determined by semiquantitative spectroscopic analysis; except, "aa" following element symbol indicates atomic-absorption analysis; "inst" indicates specific-ion electrode (F), titrimetric (S), fluorometric (U) analysis. Leaders (--) indicate no meaningful value]

Element	Range of values		Geometric mean	Number unqualified	Percent unqualified
	Minimum	Maximum			
Ag	N(0.5)	7	0.71	115	47
As-aa	N(1)	650	6.2	240	97
Au-aa	N(0.002)	3.0	0.018	215	87
B	N(10)	150	17	209	85
Ba	100	3,000	660	247	100
Be	N(1)	2	1.1	220	89
Bi	N(10)	15	--	7	2.8
Ca %	L(0.05)	3.0	0.40	243	98
Cd	N(20)	20	--	1	0.4
Co	N(5)	150	17	241	98
Cr	N(10)	300	44	182	74
Cu	5	700	210	247	100
Cs	N(10)	100	23	202	82
F-inst ¹	300	600	420	11	100
Fe %	L(0.05)	10	3.6	246	99.6
Hg-aa	N(0.02)	0.60	0.04	201	81
K-aa %	L(0.1)	5.6	2.7	244	99
La	L(20)	100	45	245	99
Li	L(1)	100	13	245	99
Mg %	0.05	3.0	0.80	247	100
Mn	15	5,000	700	247	100
Mo	N(5)	300	12	91	37
Na-aa %	N(0.1)	2.7	0.61	211	85
Ni	N(5)	150	24	214	87
Pb	N(10)	1,500	42	245	99
Rb	70	500	170	247	100
S-inst	0.005	17.4	0.89	247	100
Sb-aa	N(1)	200	2.4	140	57
Sc	L(5)	30	13	245	99
Sn	N(10)	10	--	8	3.2
Sr	N(100)	1,000	260	175	71
Te-aa	N(0.01)	4.5	0.14	241	98
Ti %	0.10	1.0	0.39	247	100
Tl-aa	0.20	4.4	1.3	247	100
U-inst	0.09	7.4	1.0	247	100
V	10	300	87	247	100
W	N(50)	100	--	9	3.6
Y	N(10)	50	20	245	99
Zn-aa	L(5)	1,900	140	246	99.6
Zr	50	300	140	247	100

¹Fluorine determined in only 11 samples.

volcanic, calcareous sedimentary, and other reactive rocks.

Surrounding geologic terrane

Porphyry copper deposits are in terranes composed of high-level intrusive rocks contemporaneous with abundant dikes, cupolas of batholiths, breccia pipes, and faults. Deposits may be covered by younger volcanic rocks or sedimentary basin fill.

Wall-rock alteration

Alteration zones (and mineral assemblages), from bottom, innermost zones outward are: sodic-calcic (oligoclase or albite, actinolite, and sphene), potassic (potassium feldspar, biotite, rutile, and pyrite or magnetite), to propylitic

Table 3. Summary statistics for 75 partly to completely oxidized rock samples from the supergene zone of porphyry copper deposits, southern Arizona, with Cu \geq 1,000 ppm (Maurice Chaffee, unpub. data). [Most concentrations in parts per million; % following an element indicates weight percent data. N, not detected at lower limit of determination, in parentheses. L, detected at concentration less than lower limit of determination, in parentheses. Mean values based on unqualified values only. Most elements determined by semiquantitative spectroscopic analysis; except, "aa" following element symbol indicates atomic-absorption analysis; "inst" indicates specific-ion electrode (F), titrimetric (S), fluorometric (U) analysis. Leaders (--) indicate no meaningful value]

Element	Range of values		Geometric mean	Number unqualified	Percent unqualified
	Minimum	Maximum			
Ag	N(0.5)	150	1.2	70	93
As-aa	N(1)	400	31	72	96
Au-aa	0.002	0.11	0.017	75	100
B	10	300	31	75	100
Ba	200	5,000	630	75	100
Be	N(1)	2	1.1	52	69
Bi	N(10)	70	--	5	6.7
Ca %	L(0.05)	0.15	0.06	39	52
Cd	N(20)	100	--	9	12
Co	N(5)	150	32	74	99
Cr	N(10)	200	38	66	88
Cu	1,000	5,000	1,500	75	100
Cs	N(10)	50	15	34	45
F-inst ¹	100	800	380	9	100
Fe %	1.0	10	4.1	75	100
Hg-aa	N(0.02)	0.64	0.05	69	92
K-aa %	1.4	5.5	2.7	75	100
La	20	200	52	75	100
Li	L(1)	30	2.7	64	85
Mg %	0.02	2.0	0.29	75	100
Mn	10	1,000	63	75	100
Mo	N(5)	300	28	66	88
Na-aa %	N(0.1)	1.8	0.18	68	91
Ni	L(5)	200	32	73	97
Pb	20	10,000	150	75	100
Rb	70	300	160	75	100
S-inst	0.10	11.7	4.1	75	100
Sb-aa	N(1)	60	4.8	63	84
Sc	5	50	14	75	100
Sn	N(10)	20	12	50	67
Sr	N(100)	1,000	250	66	88
Te-aa	N(0.01)	3,000	1.0	74	99
Ti %	0.10	1.0	0.45	75	100
Tl-aa	1.1	140	2.9	75	100
U-inst	0.13	36	1.0	75	100
V	20	300	110	75	100
W	N(50)	50	--	2	2.7
Y	N(10)	70	18	59	79
Zn-aa	L(5)	9,000	230	74	99
Zr	70	300	150	75	100

¹Fluorine determined in only 9 samples.

(oligoclase or albite, epidote or calcite, chlorite, rutile, and magnetite or pyrite). Phyllic (sericite, chlorite, rutile, and pyrite) and argillic (clay, sericite, chlorite, and pyrite) alteration may overprint early potassic assemblages. High-alumina alteration (pyrophyllite, alunite, andalusite, corundum, diaspore, clay, and sericite) may be present in upper part of some deposits. Propylitic or phyllic alteration zones commonly lie on the flanks of deposits.

Nature of ore

Ore consists of stockwork veinlets and disseminated copper minerals.

Deposit trace element geochemistry

Statistical summaries that provide elemental concentration ranges in hypogene and supergene zone rocks from

Table 4. Summary statistics for 168 partly to completely oxidized rock samples from the supergene zone of porphyry copper deposits, southern Arizona, with Cu <1,000 ppm (Maurice Chaffee, unpub. data).

[Most concentrations in parts per million; % following an element indicates weight percent data. N, not detected at lower limit of determination, in parentheses. L, detected at concentration less than lower limit of determination, in parentheses. Mean values based on unqualified values only. Most elements determined by semiquantitative spectroscopic analysis; except, "aa" following element symbol indicates atomic-absorption analysis; "inst" indicates specific-ion electrode (F), titrimetric (S), fluorometric (U) analysis. Leaders (–) indicate no meaningful value]

Element	Range of values		Geometric mean	Number unqualified	Percent unqualified
	Minimum	Maximum			
Ag	N(0.5)	15	1.0	118	70
As-aa	N(1)	450	20	166	99
Au-aa	N(0.002)	0.61	0.014	148	88
B	10	700	27	168	100
Ba	200	5,000	810	168	100
Be	N(1)	2	1.1	82	49
Bi	N(10)	20	--	10	6.0
Ca %	L(0.05)	0.5	0.07	80	48
Cd	N(20)	300	--	8	4.8
Co	N(5)	300	28	142	85
Cr	N(10)	300	51	153	91
Cu	10	700	190	168	100
Cs	N(10)	100	18	80	48
F-inst ¹	100	1,000	400	21	100
Fe %	1.0	15	3.6	168	100
Hg-aa	N(0.02)	0.60	0.06	149	89
K-aa %	0.7	5.0	2.5	168	100
La	20	100	48	168	100
Li	L(1)	50	3.0	130	77
Mg %	0.02	3.0	0.24	168	100
Mn	10	1,500	42	168	100
Mo	N(5)	300	12	118	70
Na-aa %	N(0.1)	2.3	0.20	142	85
Ni	N(5)	150	35	141	84
Pb	10	2,000	130	168	100
Rb	30	500	150	168	100
S-inst	0.030	12.7	2.7	168	100
Sb-aa	N(1)	140	3.1	141	84
Sc	L(5)	70	14	167	99
Sn	N(10)	50	13	66	39
Sr	N(100)	2,000	240	152	90
Te-aa	N(0.01)	2,000	0.48	166	99
Ti %	0.15	1.0	0.45	168	100
Tl-aa	0.55	80	2.7	168	100
U-inst	0.06	5.2	0.67	168	100
V	20	500	110	168	100
W	N(50)	100	--	13	7.7
Y	N(10)	150	17	154	92
Zn-aa	L(5)	22,000	74	166	99
Zr	70	500	160	168	100

¹Fluorine determined in only 21 samples.

porphyry copper deposits of the western United States are presented in tables 1-8. The summaries have been constructed for subsets containing samples with either $\geq 1,000$ or $< 1,000$ ppm copper; samples with copper contents $\geq 1,000$ ppm are assumed to come from copper deposits and those with copper values $< 1,000$ ppm are assumed to be from areas surrounding the deposits (outer haloes). Data summarized are from published (Chaffee, 1992; 1994) and unpublished compilations (M.A. Chaffee, unpub. data, 1995).

A comparison of mean values for hypogene samples shows that Ag, Au, Cu, Fe, Mo, S, Sb, Te, and V have significantly higher mean values in the "ore" zone, whereas chromium and manganese have significantly higher values in the areas surrounding the "ore" zones (tables 1 and 2). Other elements considered are not significantly enriched or depleted in either zone. A similar comparison of mean values for samples from areas influenced by weathering and supergene enrichment shows a significant enrichment of Ag, As, Cu, Mn, Mo, S, Sb, Te, U, and Zn in secondarily-enriched ($\geq 1,000$ ppm copper) copper zones, whereas barium and chromium are higher in the sur-

Table 5. Summary statistics for 39 rock samples from the Mount Margaret, Wash., porphyry copper deposit with Cu \geq 1,000 ppm (Chaffee, 1994).

[Most concentrations in parts per million; % following an element indicates weight percent data. N, not detected at lower limit of determination, in parentheses. L, detected at concentration less than lower limit of determination, in parentheses. Mean values based on unqualified values only. Most elements determined by semiquantitative spectroscopic analysis; except, "aa" following element symbol indicates atomic-absorption analysis; "cm" indicates colorimetric analysis. Leaders (--) indicate no meaningful value]

Element	Range of values		Geometric mean	Number unqualified	Percent unqualified
	Minimum	Maximum			
Ag	L(0.5)	5	1.1	38	97
As-aa	N(10)	50	19	9	23
Au-aa	N(0.002)	2.4	0.105	37	95
B	10	2,000	64	39	100
Ba	50	500	94	39	100
Be	N(1)	1	--	3	7.7
Bi-aa	N(1)	80	--	3	7.7
Ca %	0.05	1.0	0.60	39	100
Cd-aa	N(0.10)	1.7	0.23	25	64
Co	5	50	14	39	100
Cr	N(10)	30	16	37	95
Cu	1,000	15,000	2,000	39	100
Fe %	1.0	5.0	2.0	39	100
La	N(20)	200	38	19	49
Mg %	0.30	1.0	0.73	39	100
Mn	100	300	170	39	100
Mo	N(5)	300	38	35	90
Ni	10	70	22	39	100
Pb	N(10)	100	21	18	46
Sb-aa	N(1)	12	3.3	18	46
Sc	5	15	8.8	39	100
Sn	N(10)	10	10	9	23
Sr	N(100)	500	170	33	85
Te-aa	N(0.005)	0.60	0.035	26	67
Ti %	0.20	0.50	0.34	39	100
Tl-aa	0.05	0.70	0.21	39	100
V	50	200	81	39	100
W-cm	3	24	7.4	39	100
Y	L(10)	30	13	31	79
Zn-aa	5	170	43	39	100
Zr	30	200	69	39	100

rounding areas.

Elements with significantly higher concentrations in the supergene environment (table 3) with copper \geq 1,000 ppm, as compared to the high copper subset in the hypogene zone (table 1), include As, B, Co, Mo, Ni, S, Sb, Te, Tl, and Zn. Those significantly higher in the hypogene zone subset include Ba, Ca, Cu, Cs, F, Li, Mg, Mn, and Na.

Elemental abundances in hypogene and supergene samples from halo areas (tables 2 and 4) are very similar; As, B, Ba, Co, Ni, Pb, S, Sb, Te, Tl, and V have significantly higher mean values in the supergene zone and Ca, Cu, Cs, Li, Mg, Mn, Na, U, and Zn have higher mean values in the hypogene zone.

Samples from the Mount Margaret, Wash. deposit (tables 5 and 6), were mostly unaffected by weathering. Ag, Au, B, Cu, Mo, Pb, and W have significantly higher values in samples containing greater than 1,000 ppm copper, whereas As, Cd, Sb, Sr, and Te are higher in samples from outside the "ore" zone. Similarly, samples from the Kalamazoo deposit, Ariz. (tables 7 and 8), were almost unaffected by weathering. Ag, Au, B, Ce, Cu, F, Li, Mg, Mo, S, Sb, Se, V, and CO₂ abundances are significantly higher in the subset of samples that contains \geq 1,000 ppm copper, whereas Fe, Hg, Mn, Pb, Rb, Te, Tl, and Zn abundances are greater in samples from areas surrounding the "ore" zone.

Ore samples from Tanamá (table 9), Puerto Rico (Cox, 1985), with more than 4,000 ppm copper, have different metal concentrations in different mineral zones. The potassically altered chalcopyrite-magnetite zone (table 9) has higher manganese (700 ppm) and zinc (60 ppm) than the phyllic-altered chalcopyrite-pyrite zone (table 10), which has higher sulfur (2.3 weight percent) and selenium (6 ppm).

Table 6. Summary statistics for 28 rock samples from the Mount Margaret, Wash., porphyry copper deposit with Cu <1,000 ppm (Chaffee, 1994).

[Most concentrations in parts per million; % following an element indicates weight percent data. N, not detected at lower limit of determination, in parentheses. L, detected at concentration less than lower limit of determination, in parentheses. Mean values based on unqualified values only. Most elements determined by semiquantitative spectroscopic analysis; except, "aa" following element symbol indicates atomic-absorption analysis; "cm" indicates colorimetric analysis. Leaders (–) indicate no meaningful value]

Element	Range of values		Geometric mean	Number unqualified	Percent unqualified
	Minimum	Maximum			
Ag	N(0.5)	3	0.70	18	64
As-aa	N(10)	100	23	12	43
Au-aa	N(0.002)	0.15	0.033	26	93
B	10	>2,000	37	27	96
Ba	30	200	86	28	100
Be	N(1)	N(1)	--	0	0
Bi-aa	N(1)	1	--	1	3.6
Ca %	L(0.05)	1.0	0.73	25	89
Cd-aa	N(0.10)	6.7	0.39	7	25
Co	N(5)	30	11	26	93
Cr	10	20	13	28	100
Cu	100	700	340	28	100
Fe %	0.7	5.0	1.9	28	100
La	N(20)	100	33	4	14
Mg %	0.10	1.0	0.57	28	100
Mn	50	500	150	28	100
Mo	N(5)	200	20	18	64
Ni	L(5)	30	17	27	96
Pb	N(10)	30	11	8	29
Sb-aa	N(1)	84	6.2	9	32
Sc	5	15	7.3	28	100
Sn	N(10)	20	11	6	21
Sr	N(100)	500	220	23	82
Te-aa	N(0.005)	0.80	0.062	18	64
Ti %	0.20	0.50	0.30	28	100
Tl-aa	N(0.05)	0.65	0.25	26	93
V	50	100	67	28	100
W-cm	2	15	5.6	28	100
Y	N(10)	20	11	14	50
Zn-aa	N(5)	1,100	40	27	96
Zr	50	500	87	28	100

Ore and gangue mineralogy and zonation

Primary minerals include chalcopyrite + pyrite ± bornite ± molybdenite. Gangue and alteration minerals are potassic (quartz + K-feldspar + biotite + anhydrite), grading outward to propylitic (albite, chlorite, epidote, calcite). Plagioclase in these assemblages can neutralize acid. Late-stage assemblages, which have significant acid generation capacity, include quartz + sericite + clay + pyrite ± alunite ± pyrophyllite. Assemblages commonly are superimposed. Late veins of chalcopyrite, bornite, enargite, tetrahedrite, galena, sphalerite, and barite are present in some deposits.

Important exceptions: Most porphyry copper-gold deposits contain chalcopyrite + magnetite ± bornite (Cox and Singer, 1992). Pyrite is abundant only in the outer phyllic alteration halo, or in the upper part of some deposits, in late-stage phyllic-altered rock. A breccia pipe in Oregon with porphyry copper affinities contains bornite, chalcopyrite, and essentially no pyrite; the main ferrous iron mineral is siderite (Stone, 1992).

Mineral characteristics

Porphyry has closely spaced quartz and feldspar phenocrysts in a fine grained, aplitic quartz-feldspar groundmass. Ore minerals are present in stockwork veinlets and as disseminated sulfide grains.

Secondary mineralogy

Weathered outcrops in high pH environments include copper carbonate, oxide, and silicate minerals. Most deposits that include abundant pyrite, create low pH environments in which leaching is intense; outcrops are greatly depleted

Table 7. Summary statistics for 121 rock samples from the Kalamazoo porphyry copper deposit, Ariz., with Cu \geq 1,000 ppm (Chaffee, 1992).

[Most concentrations in parts per million; % following an element indicates weight percent data. N, not detected at lower limit of determination, in parentheses. L, detected at concentration less than lower limit of determination, in parentheses. Mean values based on unqualified values only. Most elements determined by semiquantitative spectroscopic analysis; except, "aa" following element symbol indicates atomic-absorption analysis; xrf, indicates X-ray fluorescence analysis; inst indicates volumetric analysis (CO₂), specific-ion electrode (F), titrimetric (S), colorimetric (Se). Leaders (--) indicate no meaningful data]

Element	Range of values		Geometric mean	Number unqualified	Percent unqualified
	Minimum	Maximum			
Ag	N(0.5)	15	1.1	59	49
Al-xrf %	4	9.5	6.5	121	100
As-cm	N(10)	1,200	16	49	40
Au-aa	N(0.02)	0.40	0.053	92	76
B	N(20)	200	49	22	18
Ba	100	2,000	660	121	100
Be	N(1.5)	3	1.7	81	67
Bi	N(10)	10	--	1	0.8
CO ₂	N(0.0003)	3.6	0.63	119	98
Ca %	0.07	3.0	0.56	121	100
Cd-aa	N(0.10)	25	0.37	102	84
Ce	N(200)	200	--	4	3.3
Co	L(5)	100	15	120	99
Cr	5	300	21	121	100
Cs	N(20)	30	8.3	27	22
Cu	1,000	30,000	2,800	121	100
F-inst	100	940	410	121	100
Fe %	0.7	7.0	2.3	121	100
Ga	15	30	19	121	100
Hg-aa	0.02	0.80	0.08	121	100
K-aa %	1.0	5.0	2.5	121	100
La	N(50)	100	61	61	50
Li-aa	15	1,100	47	121	100
Mg %	0.20	1.5	0.63	121	100
Mn	7	700	100	121	100
Mo	N(3)	1,000	22	104	86
Na-aa %	0.10	3.2	0.92	121	100
Nb	N(10)	30	12	57	47
Ni	L(5)	150	15	116	96
P-xrf	L(440)	2,400	1,100	106	88
Pb	N(10)	70	14	95	79
Rb	20	200	55	121	100
S-inst	0.29	9.4	1.69	121	100
Sb-cm	N(1)	1,500	10	49	40
Sc	L(5)	30	10	120	99
Se-inst	0.10	16	2.7	121	100
Si-xrf %	21	35	31	121	100
Sn	N(10)	15	10	15	12
Sr	50	700	150	121	100
Te-aa	N(0.10)	2.0	0.30	16	13
Ti %	0.15	0.50	0.26	121	100
Tl-aa	N(0.20)	4.2	0.47	104	86
V	30	300	90	121	100
W	N(100)	L(100)	--	0	0
Y	N(10)	70	23	97	80
Yb ¹	N(1)	7	2.3	105	95
Zn-aa	N(5)	1,100	21	118	98
Zr	30	300	93	121	100

¹Yb determined in only 110 samples.

Table 8. Summary statistics for 162 rock samples from the Kalamazoo porphyry copper deposit, Ariz., with Cu <1,000 ppm (Chaffee, 1992).

[Most concentrations in parts per million; % following an element indicates weight percent data. N, not detected at lower limit of determination, in parentheses. L, detected at concentration less than lower limit of determination, in parentheses. Mean values based on unqualified values only. Most elements determined by semiquantitative spectroscopic analysis; except, "aa" following element symbol indicates atomic-absorption analysis; xrf, indicates X-ray fluorescence analysis; inst indicates volumetric analysis (CO₂), specific-ion electrode (F), titrimetric (S), colorimetric (Se). Leaders (–) indicate no meaningful data]

Element	Range of values		Geometric mean	Number unqualified	Percent unqualified
	Minimum	Maximum			
Ag	N(0.5)	3.0	0.83	13	8.0
Al-xrf %	3.3	11	5.5	162	100
As-cm	N(10)	80	15	46	28
Au-aa	N(0.02)	1.2	0.034	75	46
B	N(20)	70	28	15	9.3
Ba	70	3,000	590	162	100
Be	N(1.5)	7	2.0	140	86
Bi	N(10)	30	--	1	0.6
CO ₂ -inst ¹	N(0.0003)	2.3	0.48	161	100
Ca %	0.05	3.0	0.46	162	100
Cd-aa	N(0.10)	2.0	0.33	141	87
Ce	N(200)	700	--	2	1.2
Co	N(5)	70	10	158	98
Cr	5	150	17	162	100
Cs	N(20)	30	7.1	45	28
Cu	10	700	270	162	100
F-inst	140	840	310	162	100
Fe %	0.3	10	3.3	162	100
Ga	7	30	18	162	100
Hg-aa	0.02	0.65	0.11	162	100
K-aa %	0.8	4.6	2.5	162	100
La	N(50)	300	62	80	49
Li-aa	10	770	31	162	100
Mg %	0.05	2.0	0.54	162	100
Mn	7	1,500	200	162	100
Mo	N(3)	30	4.2	96	59
Na-aa %	0.10	2.6	0.91	162	100
Nb	N(10)	30	15	110	68
Ni	N(5)	70	13	153	94
P-xrf	L(440)	2,200	1,000	152	94
Pb	N(10)	1,000	27	151	93
Rb	30	200	96	162	100
S-inst	0.010	22	0.98	161	99
Sb-cm	N(1)	20	2.1	80	49
Sc	N(5)	30	11	160	99
Se-inst	L(0.10)	10	1.0	159	98
Si-xrf %	20	37	31	162	100
Sn	N(10)	10	--	3	1.9
Sr	30	700	120	162	100
Te-aa	N(0.10)	3.5	0.62	63	39
Ti %	0.03	1.0	0.27	162	100
Tl-aa	L(0.20)	3.3	0.74	160	99
V	L(7)	150	71	160	99
W	L(100)	200	--	5	3.1
Y	L(10)	150	28	148	91
Yb ²	N(1)	10	3.9	140	86
Zn-aa	N(5)	900	38	160	99
Zr	30	500	110	162	100

¹CO₂ determined in only 161 samples.

²Yb determined in only 143 samples.

Table 9. Summary statistics for 18 samples of mostly unoxidized rocks from the chalcopyrite-magnetite zone of the Tanamá porphyry copper deposit, Puerto Rico. Data, in ppm unless otherwise noted, from Cox (1985); N, not detected at indicated abundance.

Element	Minimum	Maximum	Median	Number unqualified	Percent unqualified
Ag	1	5	1.5	18	100
Au	0.2	0.95	0.36	18	100
Ba	150	500	200	18	100
Cu	4,400	15,600	6,700	18	100
Co	7	30	15	18	100
Cr	20	1,000	50	18	100
Mn	150	>5,000	700	18	100
Mo	N5	70	15	14	78
Ni	10	70	15	18	100
Pb	4	21	8	18	100
S %	0.4	8	1.5	18	100
Se	2	8	3	18	100
Te	<0.1	0.7	0.12	9	50
Ti	<0.2	0.76	0.3	12	67
Zn	17	2,300	60	18	100

Table 10. Summary statistics for 15 samples of mostly unoxidized rocks from the chalcopyrite-pyrite zone of the Tanamá porphyry copper deposit, Puerto Rico. Data, in ppm unless otherwise noted, from Cox (1985); N, not detected at indicated abundance.

Element	Minimum	Maximum	Median	Number unqualified	Percent unqualified
Ag	0.7	2	1.5	15	100
Au	0.18	0.65	0.36	15	100
Ba	150	500	200	15	100
Cu	4,300	13,000	8,400	15	100
Co	10	30	15	15	100
Cr	N20	70	30	14	93
Mn	50	700	200	15	100
Mo	N5	70	5	8	57
Ni	10	30	15	15	100
Pb	2	13	7	15	100
S %	0.6	5.6	2.3	15	100
Se	4	9	6	8	53
Te	<0.1	0.79	0.11	8	50
Ti	<0.2	0.68	0.34	10	67
Zn	9	270	36	15	100

Table 11. Summary statistics for soil samples from the B horizon above two distinct mineral zones in the Tanamá porphyry copper deposit, Puerto Rico. Data, in ppm, from Learned and others (1992).

Element	Magnetite zone				Pyrite zone			
	Maximum	Minimum	Median	Number of samples	Maximum	Minimum	Median	Number of samples
Cu	2,000	150	510	12	400	71	160	12
Pb	19	5	10	12	23	1	4	12
Zn	17	2	8	12	11	<1	5	12
Mo	50	<5	5	12	300	<5	20	12
Cd	2.4	0.7	1.4	12	3.5	0.4	1	12

in copper; other metals may be similarly affected. Leached copper is transported downward and deposited as secondary sulfide minerals at the water table or paleowater table. Deposits of secondary sulfide minerals contain chalcocite, covellite, as well as other Cu_2S and CuS minerals that replace pyrite and chalcopyrite.

Topography, physiography

Deposits are mainly in mountainous terrain, but in the southwestern United States they commonly are found partially or completely buried under Cenozoic basin fill deposits.

Hydrology

Potassic zone is commonly weakly jointed; phyllic and argillic zones are generally highly jointed and permeable to ground water.

Mining and milling methods

Deposits are generally mined by open pit methods; on average, about 1.49 tonnes of waste rock and overburden must be removed to obtain one tonne of ore (Phillips and Niemuth, 1993). Deep deposits are exploited by underground block caving. Oxidized ore buried by Cenozoic alluvium may be exploited by in-place leaching. Experiments with in-place leaching are being carried out at the Santa Cruz, Ariz., deposit which is buried beneath as much as 445 m of Cenozoic basin-fill sediment and conglomerate (Dillard, 1995).

During open pit mining, rock with low copper content that must be removed to recover ore is placed on waste dumps. Slightly higher grade rock is placed in dumps and leached with acid so that copper can be recovered from solutions collected at the toe of the dump. Richer ore is treated in several ways depending on its mineralogy. To recover copper from chalcopyrite ore, the ore is crushed and ground, mixed with organic compounds and water, and frothed by a stream of air bubbles Parsons (1933). Chalcopyrite adheres to surfaces of bubbles and floats to the surface where it is separated from pyrite and silicate and other minerals. Fine waste material is then circulated to tailings ponds. Chalcopyrite concentrate is roasted in a smelter to remove its sulfur. The resulting copper matte, containing about 99 weight percent copper, is sent to a refinery where it is dissolved electrolytically and reprecipitated as cathode copper, about 99.99 percent pure. Sulfur, produced in the smelter, is converted to acid and commonly recycled to leach copper from dumps.

Deeply oxidized porphyry copper deposits commonly have a leached, copper-poor cap underlain by an enriched zone amenable to acid leaching and recovery of copper by solvent extraction and electrowinning (SX-EW). This process (Lynch and others, 1994) produces cathode copper directly without fine grinding and attendant production of tailings, and without smelting and attendant release of sulfur-rich gas. Ore is leached in place, or mined, crushed, and placed on a leach pad on an impermeable base surface. Acid is applied at the top and copper-rich solution is extracted at the bottom. This solution is mixed with a synthetic organic compound that selectively extracts copper. Barren acid leach solutions are returned to the leach pad and the organic compound is mixed with concentrated acid that recovers copper. The organic compound is returned and mixed with more copper-rich leach solution. The copper-rich acid is sent to the electrowinning cell where pure copper is electroplated onto a cathode. Sulfur resulting from this process is converted to acid and returned to the leach pad.

Application of the SX-EW process depends on ore mineralogy (Lynch and others, 1994). Ore that contains azurite, malachite, tenorite, brochantite, and atacamite can be leached with dilute sulfuric acid. Ore with chalcocite, covellite, cuprite, native copper, and bornite can be leached with acid-ferric iron solutions into which sulfur-oxidizing bacteria are introduced. Chalcopyrite is leached slowly by strong acids and bacteria. Ore that contains acid-consuming minerals such as calcite can be leached with ammonia. Production of by-product molybdenum or gold by acid leaching copper-molybdenum or copper-gold porphyry ore has not yet been achieved, but might be possible in the future.

ENVIRONMENTAL SIGNATURES

Drainage signatures and metal mobility from solid mine wastes

Elements in surface materials may be remobilized by chemical leaching or mechanical weathering processes; those whose abundances in rock or soil are elevated can become similarly elevated in derivative materials. All elements present are transported away from porphyry system exposures by mechanical erosion; in addition, elements can be remobilized from subsurface rock by flowing ground water. However, three factors particularly influence the chemical environment in and around porphyry copper deposits: (1) host-rock chemistry, (2) the level of erosion in a given deposit, (3) the abundances of elements and various mineral species at a given erosion level.

The chemical, as well as the physical, nature of the host rocks in the vicinity of porphyry copper deposits influence the extent of associated chemical dispersion. Chemically reactive host rocks, such as limestone and dolomite, react with acidic solutions containing elements, such as copper and zinc, that are mobile in the low-pH environment commonly associated with a weathering porphyry copper deposit. Most other host-rock lithologies are relatively non-reactive to low-pH solutions and do not much affect solution-borne elements.

Porphyry copper deposit genesis typically produces zones containing concentrations of various elements and minerals (Chaffee, 1976a, 1982). Some elements and minerals tend to be concentrated in the core of a deposit, some in the main chalcopyrite zone, some in the pyrite halo, and some in the outermost parts of a deposit. Data in tables 1-8, for instance, indicate that the outer halo around the chalcopyrite zone may be enriched in the elements Ag, As, Au, B, Cu, Fe, B, Mo, Pb, S, Se, Te, Tl, and (or) Zn, whereas the inner parts of the same system have different abundances and distributions of ore-related elements. Thus, the environmental effects of a given porphyry copper deposit depend on the level of erosion.

Porphyry copper deposits commonly contain significant pyrite abundances. Pyrite is usually concentrated in a zone that is generally at the outer edge of the chalcopyrite zone. During weathering, pyrite decomposition produces a low pH environment and many mineral deposit-related elements react with the resulting acidic solutions and, in the absence of carbonate rocks, (1) co-precipitate locally with iron-oxide phases (for instance, molybdenum and tellurium), (2) form new minerals (for instance, chalcocite, covellite, native copper, malachite), or (3) precipitate on unweathered sulfide grains (chalcocite, covellite). All of these reactions significantly restrict dispersion of the elements affected. This process results a zone of supergene-enriched metals. In the absence of significant pyrite, weathering leaches Cu, Mo, and Zn, as well as B, Co, Mn, S, Se and major rock-forming elements such as Ca, Mg, and Na, from near-surface rocks and disperses them into the surrounding environment.

The interaction between a porphyry copper deposit and the environment is illustrated by a stream in the Globe mining district, Ariz. that was blocked by mill tailings, causing a lake to form. Water from this lake entered an alluvial aquifer by seepage; the aquifer and a stream to the north were contaminated. The results, as reported by Eychaner (1991) and Stollenwerk (1994), represent the chemical signature of a pyrite-rich porphyry copper deposit in the natural environment, although the pH in this case is much lower, and the dissolved metal content much higher, than would be expected in a natural weathering situation. The most contaminated ground water in the aquifer had a pH of 3.3, and contained about 9,600 mg/l sulfate, 2,800 mg/l iron, 300 mg/l aluminum, and 190 mg/l copper. As the plume traveled north through the aquifer, the concentration of constituents decreased as the plume interacted with alluvium and was diluted by uncontaminated water (ground water flowing upwards from lower basin-fill, water in uncontaminated streams that join the contaminated wash, and surface rain water). In all cases, mixing was not necessarily instantaneous, and uncontaminated water could flow parallel to the plume for hundreds of meters before mixing was complete. The large concentration of sulfate in acidic ground water has a significant effect on the speciation of aqueous cations: about 50 percent of Ca, Mg, Fe, Mn, Cu, Co, Ni, and Zn, and more than 80 percent of the aluminum, are transported as sulfate-ion pair complexes. The acid-water front, pH <5, has advanced through alluvium, which contained about 0.4 weight percent carbonate minerals, at a rate of 0.2 to 0.3 km/yr during the past several decades. One of the reactions modeled by Stollenwerk (1994) is dissolution of calcite and dolomite by acidic water and precipitation of large amounts of calcium as gypsum. Stollenwerk (1994) concluded that aluminum and pH exhibit the greatest potential for continued adverse effects to ground water quality. In a work plan written by Eychaner (unpublished data, 1989), he states, "In ground water systems the movement of acidic water is retarded by chemical reactions with the aquifer material, but the same reactions transform the aquifer and decrease its capacity to retard future contamination."

Soil, sediment signatures prior to mining

Data from Tanamá, Puerto Rico (Learned and others, 1992) show different metal abundances in the B-horizon of residual soil over magnetite-rich (1.4 weight percent S) and pyrite-rich (2.5 weight percent S) copper ore zones (table 11). These data illustrate how acid, which is released as pyrite oxidizes, leaches metals from soil. An exception is molybdenum, which is not readily leached in low pH environments. Chaffee and others (1981) indicate that stream sediment from the area draining the unmined Red Mountain porphyry copper deposit in arid southeastern Arizona contains elevated abundances of molybdenum, lead, and tellurium. The Mineral Butte and Vekol, Ariz., deposits are other, arid-climate porphyry copper deposits for which pre-mining geochemical data are available. Chaffee (1976b; table 1 and 1977; table 3) presents ranges, backgrounds, and geochemical anomaly thresholds for Mn, Cd, Cu, Co, F, Au, Pb, Bi, Hg, Mo, Ag, and Zn abundances in bedrock and residual soil samples collected in the vicinity of these deposits. Abundances of most of these elements are elevated in the vicinity of these deposits relative to

those characteristic of other geologic environments; these elevated abundances identify appropriate baseline geochemical values that may be useful in setting remediation standards for mines associated with this deposit type.

Potential environmental concerns associated with mineral processing

Acid drainage from waste dumps and dust from mill tailings are among the potential environmental concerns associated with mineral processing. Very few concerns are associated with SX-EW processing.

Smelter signatures

No data specific to the environmental effects of smelting ore from deposits of this type were identified. However, copper sulfide minerals are typically smelted and may produce SO₂-rich and metal-rich emissions, which may increase acidity and foster accumulation of heavy metals in downwind areas.

Climate effects on environmental signatures

The effects of various climate regimes on the geoenvironmental signature specific to porphyry copper deposits are not known. However, in most cases the intensity of environmental impact associated with sulfide-mineral-bearing mineral deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell. Present surface and near-surface chemical relations and mineral assemblages may reflect pre-existing (wetter) climate in the southwest United States.

Geoenvironmental geophysics

Detailed induced polarization and (or) resistivity or electromagnetic surveys can identify low resistivity rocks associated with porous and permeable, clay-altered sulfide-mineral-bearing veins, fractures and faults, and breccia pipes that may be a source of acidic, metal-bearing water that results from oxidation of iron or copper sulfide minerals (King and Pesowski, 1993). Oxidation of sulfide minerals may create thermal anomalies identifiable by infrared surveys, shallow heat-flow probes, or self potential (Strangway and Holmer, 1966; Corry, 1985; Corwin, 1990). Acid- or metal-bearing water has low resistivity that can be identified with electromagnetic or direct current induced polarization and (or) resistivity surveys and ground penetrating radar (Greenfield and Stoyer, 1976; Davis and Annan, 1992; King and Pesowski, 1993). Structural and stratigraphic features such as bedrock topography, buried channels, permeable fault zones, and aquitards that affect water flow away from mine areas may be studied with electromagnetic, direct current resistivity, seismic refraction, and gravity surveys (Paterson 1995). Water flow may be monitored using self potential techniques (Corwin, 1990). Carefully designed and interpreted self potential surveys also may be useful in defining reduction-oxidation centers in tailings (Paterson, 1995). Remote sensing images derived from satellite or airborne surveys can be used to identify the distribution of alteration assemblages, which in turn help identify areas that may be sources of acidic and metal-bearing water; images derived from airborne surveys, such as AVIRIS, also may indicate the distribution of minerals that provide acid buffering capacity. Remote sensing can also be used to evaluate effects related to large scale open pit mining.

REFERENCES CITED

- Abrams, M.J., Brown, David, Lepley, Larry, and Sadowski, Ray, 1983, Remote sensing for porphyry copper deposits in southern Arizona: *Economic Geology*, v. 78, p. 591-604.
- Birnie, R.W., and Francica, J.R., 1981, Remote detection of geobotanical anomalies related to porphyry copper mineralization: *Economic Geology*, v. 76, p. 637-647.
- Carlson, J.E., and Mabey, D.R., 1963, Gravity and aeromagnetic maps of the Ely area, White Pine County, Nevada: U.S. Geological Survey Geophysical Investigations Map GP-392, scale 1:250,000.
- Chaffee, M.A., 1976a, The zonal distribution of selected elements above the Kalamazoo porphyry copper deposit, San Manuel district, Pinal County, Arizona: *Journal of Geochemical Exploration*, v. 5, no. 2, p.145-165.
- _____, 1976b, Geochemical exploration techniques based on distribution of selected elements in rocks, soils, and plants, Mineral Butte copper deposit, Pinal County, Arizona: U.S. Geological Survey Bulletin 1278-D, p. D1-D55.

- _____, 1977, Geochemical exploration techniques based on distribution of selected elements in rocks, soils, and plants, Vekol porphyry copper deposit, Pinal County, Arizona: U.S. Geological Survey Bulletin 1278-E, p. E1-E78.
- _____, 1982, A geochemical study of the Kalamazoo porphyry copper deposit, Pinal County, Arizona, *in* Titley, S.R., ed., *Advances in Geology of the Porphyry Copper Deposits, Southwestern North America*: Arizona University Press, Tucson, p. 211-224.
- _____, 1992, Data for four drill holes, Kalamazoo porphyry copper deposit, Pinal County, Arizona: U.S. Geological Survey Open-File Report 92-238-A, 50 p., and Report 92-238-B (diskette).
- _____, 1994, Data for four drill holes, Mount Margaret copper-molybdenum-gold deposit, Skamania County, Washington: U.S. Geological Survey Open-File Report 94-2-A, 10 p., and Report 94-2-B (diskette).
- Chaffee, M.A., Hill, R.H., Sutley, S.J., and Waterson, J.R., 1981, Regional geochemical studies in the Patagonia Mountains, Santa Cruz County, Arizona: *Journal of Geochemical Exploration*, v. 14, p. 135-153.
- Corry, C.E., 1985, Spontaneous polarization associated with porphyry sulfide mineralization: *Geophysics*, v. 50, no. 6 p. 1020-1034.
- Corwin, R.F., 1990, The self-potential method for environmental and engineering applications, *in* Ward, S.H., ed., *Geotechnical and environmental geophysics*, v.I: Tulsa, OK, Society of Exploration Geophysicists, p.127-145.
- Cox, D.P., 1985, Geology of the Tanama and Helecho porphyry copper deposits and their vicinity, Puerto Rico: U.S. Geological Survey Professional Paper 1327, 59 p.
- _____, 1986, Descriptive model of porphyry copper, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models*: U.S. Geological Survey Bulletin 1693, p. 76.
- _____, 1992, Descriptive model of distal disseminated Ag-Au deposits, *in* Bliss, J.D., ed., *Developments in mineral deposit modeling*: U.S. Geological Survey Bulletin 2004, p. 20-22.
- Cox, D.P., and Singer, D.A., 1986, *Mineral deposit models*: U.S. Geological Survey Bulletin 1693, 379 p.
- _____, 1992, Distribution of gold in porphyry copper deposits, *in* DeYoung, J.H., Jr., and Hammarstrom, J.M., eds., *Contributions to commodity geology research*: U.S. Geological Survey Bulletin 1877, p. C1-C14.
- Davis, J.L., and Annan, A.P., 1992, Applications of ground penetrating radar to mining, groundwater, and geotechnical projects: selected case histories: *in* Pilon, J., *Ground Penetrating Radar: Geological Survey of Canada, Paper 90-4*, p. 49-55.
- Dillard, Gary, 1995, Industry-government project has big potential: *Southwestern Paydirt*, no. 668, Feb. 1995, p. 4A-9A.
- Elliot, C.L., and MacLean, H., 1978, Induced-polarization depth penetration in exploring for porphyry coppers: *Arizona Geological Society Digest*, v. 11, p. 37-48.
- Eychaner, J.H., 1991, The Globe, Arizona, research site--contaminants related to copper mining in a hydrologically integrated environment, *in* Mallard, G.E., and Aronson, D.A., eds., *U.S. Geological Survey Toxic Substances Hydrology Program--Proceedings of the technical meeting, Monterey, California, March 11-15, 1991*: U.S. Geological Survey Water-Resources Investigations Report 91-4034, p. 439-447.
- Grant, F.S., 1985, Aeromagnetism, geology, and ore environments: *Geoexploration*, v. 23, no. 3, p. 303-362.
- Greenfield, R.J., and Stoyer, C.H., 1976, Monitoring ground-water contamination with geophysical methods: *Society of Mining Engineers, Transactions, American Institute of Mining Engineering*, v. 260, p. 20-28.
- Gustafson, L.B., and Hunt, J.P., 1975, The porphyry copper deposit at El Salvador, Chile: *Economic Geology*, v. 70, p. 857-912.
- King, A., and Pesowski, 1993, Environmental applications of surface and airborne geophysics in mining: *Canadian Institute of Mining and Metallurgy Bulletin*, v. 86, p. 58-67.
- Knepper, D.H., 1989, Mapping hydrothermal alteration with Landsat thematic mapper data, *in* Lee and others, eds., *Mineral deposits of North America*, v. 1, *Remote sensing in exploration geology, Field trips for the 29th International Geological Congress*: Washington, DC, American Geophysical Union, p. 13-21.
- Lanier, George, John, E.C., Swenson, A.J., Reid, Julia, Bard, C.E., Caddy, S.W., and Wilson, J.C., 1978, General geology of the Bingham mine, Bingham Canyon, Utah: *Economic Geology*, v. 73, p. 1228-1241.
- Learned, R.E., Pierce, H.A., and Pérez, Ileana, 1992, Analytical results and sample locality map of soil samples from the Tanama and Helecho porphyry copper deposits district, Municipios of Utuado and Adjuntas, Puerto Rico: U.S. Geological Survey Open-File Report 93-179, 34 p.
- Lowell, J.D., and Guilbert, J.M., 1970, Lateral and vertical alteration-mineralization zoning in porphyry copper deposits: *Economic Geology*, v. 65, p. 363-408.

- Lynch, A.J., Taylor, Alan, and Avendaño Varas, Carlos, 1994, Solvent extraction boom in Latin America: *Engineering and Mining Journal*, Dec. 1994, p. 18-21.
- Parsons, A.B., 1933, The porphyry coppers: New York, American Institute of Mining and Metallurgical Engineers, 581 p.
- Paterson, 1995, Application of geophysical methods to the detection and monitoring of acid mine drainage: *in* Bell, R.S., Proceedings of the Symposium on the application of geophysics to engineering and environmental problems: Orlando, Florida, April 23-26, Environmental and Engineering Geophysical Society, p. 181-189.
- Pelton, W.H., and Smith, P.K., 1976, Mapping porphyry copper deposits in the Philippines with IP: *Geophysics*, v. 41, no. 1, p. 106.
- Phillips, K.A., and Niemuth, N.J., 1993, The primary copper industry of Arizona in 1991: Phoenix, Arizona, Department of Mines and Mineral Resources, Special Report No. 18, 53 p.
- Raines, G.L., 1978, Porphyry copper exploration model for northern Sonora, Mexico: *U.S. Geological Survey Journal of Research*, v. 6, no. 1, p. 51-58.
- Singer, D.A., and Mosier, D.L., 1981, The relation between exploration economics and the characteristics of mineral deposits, *in* Ramsey, J.B., ed., *The economics of exploration for energy resources*: Greenwich, Conn., Jai Press Inc., p. 313-326.
- Singer, D.A., Mosier, D.L., and Cox, D.P., 1986, Grade-tonnage model of porphyry copper, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models*: U.S. Geological Survey Bulletin 1693, p. 77-81.
- Stollenwerk, K.G., 1994, Geochemical interactions between constituents in acidic ground water and alluvium in an aquifer near Globe, Arizona: *Applied Geochemistry*, v. 9, p. 353-369.
- Stone, B.G., 1992, The Bornite project, Oregon: geology, technology and serendipity: Northwest Mining Association 1992 Short Course, Tucson, Ariz., and Spokane, Wash., Porphyry copper model--regional talks and settings, 22 p.
- Strangway, D.W., and Holmer, R.C., 1966, The search for ore deposits using thermal radiations: *Geophysics*, v. 31, p. 225-224.
- Titley, S.R., 1982, *Advances in the geology of porphyry copper deposits, southwestern North America*: Tucson, University of Arizona Press, 555 p.
- Turner, R.L., Raines, G.L., Kleinkopf, M.D., 1982, Regional northeast-trending structural control of mineralization, northern Sonora, Mexico: *Economic Geology*, no. 77, v. 1, p. 25-37.

CU, AU, AND ZN-PB SKARN DEPOSITS
(MODELS 18b,c; Cox and Theodore, 1986; Cox, 1986; Theodore and others, 1991)

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INTRODUCTION

The general description of skarns given below is also applicable to the SN and (or) W skarn and replacement deposits and Fe skarn deposits geoenvironmental models.

Skarns are coarse-grained metamorphic rocks composed of calcium-iron-magnesium-manganese-aluminum silicate minerals (commonly referred to as "calcsilicate" minerals) that form by replacement of carbonate-bearing rocks (in most cases) during contact or regional metamorphism and metasomatism. The majority of the world's major skarn deposits are thought to be related to hydrothermal systems (Einaudi and others, 1981). Skarns can be barren or contain metals with economic value. Skarn deposits are important sources of base and precious metals as well as tin, tungsten, and iron. Skarns are relatively high-temperature mineral deposits related to magmatic-hydrothermal activity associated with granitoid plutons in orogenic tectonic settings; skarns generally form where a granitoid pluton has intruded sedimentary strata that include limestone or other carbonate-rich rocks. The processes that lead to formation of all types of skarn deposits include: (1) isochemical contact metamorphism during pluton emplacement, (2) prograde metasomatic skarn formation as the pluton cools and an ore fluid develops, and (3) retrograde alteration of earlier-formed mineral assemblages. Deposition of ore minerals accompanies stages 2 and 3. Skarn deposits are typically zoned mineralogically with respect to pluton contacts, original lithology of host rocks, and (or) fluid pathways. Later petrogenetic stages may partly or completely obliterate earlier stages of skarn development. Skarn deposits commonly are also associated with many other types of magmatic-hydrothermal deposits in mineral districts. In fact, distinction between skarn and other deposit types is not always apparent, and in many districts, skarns form an intermediate "zone" between porphyry deposits in the center of mining districts and peripheral zones of polymetallic vein and replacement and distal disseminated deposits. In many cases, geochemical signatures in stream sediment or water may reflect mixtures of several deposit types. -

Skarns are classified as calcic if the protolith was limestone and as magnesian if the protolith was dolomite; they are also classified by the most economically important metal present (copper, iron, lead-zinc, gold, tin, tungsten, etc.). Each class of skarn deposit has a characteristic, though not necessarily unique, size, grade, tectonic setting, granitoid association, and mineralogy (Einaudi and Burt, 1982; Einaudi and others, 1981; Meinert, 1983). Not surprisingly, therefore, the various classes of skarn deposits have different geochemical signatures and oxidation-sulfidation states. Most economic skarn ore is present as exoskarn, which forms in carbonate rock that hosts a mineralizing intrusion. Endoskarn, which is variably developed on the intrusion side of intrusion-wallrock contacts, can be important when fluid flow was directed into the intrusion or channelized along the intrusion-wall rock contact.

Separate geoenvironmental models for three groups of skarn deposits are presented below: (1) base and precious metal, (2) tin and tungsten, and (3) iron skarns. These groupings are based on geologic setting, associated igneous rock compositions, skarn mineralogy and sulfide mineral content, and characteristic geochemical and geophysical signatures (fig. 1). Differences among these groups of deposits indicate different potentials for acid mine drainage and differences in geoavailability of potentially toxic substances. For example, the principal ore minerals in base and precious metal skarns are sulfide minerals, whereas the principal tin and tungsten ore minerals are the oxide and tungstate minerals cassiterite and scheelite, respectively. Data tables illustrate observed ranges of composition for skarn, stream-sediment, soil, water, and mine waste. Much of these data reflect the authors' unpublished and published work in north-central Nevada and in southwestern Montana. Both areas contain examples of skarn deposits from each model group. No new data were acquired for this model development effort, but some previously unpublished geochemical data are included. These models are preliminary compilations based on existing data from a variety of sources.

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

These deposits consist of base- and precious-metal minerals in calcsilicate rocks. Copper skarn generally consists of chalcopyrite in contact metasomatic rocks. Zinc-lead skarns are composed of sphalerite and galena in calc-silicate rocks that may represent contact metasomatism by nearby granitoid intrusions or they may form hundreds of meters from intrusions inferred to be sources of metasomatizing fluids. Gold-bearing skarns are generally calcic exoskarns

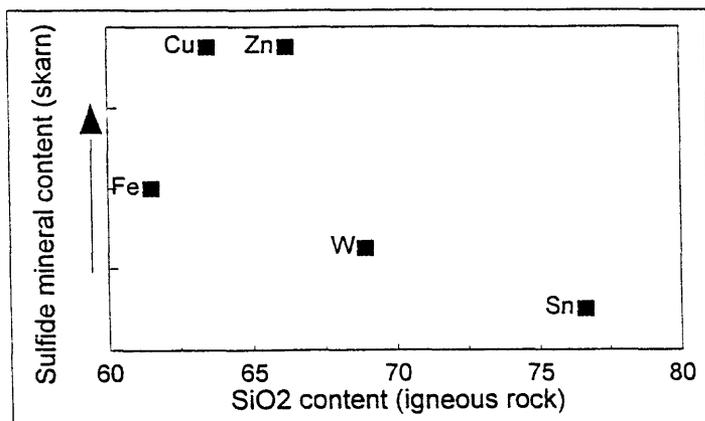


Figure 1. Schematic diagram showing relative positions of different classes of skarns as a function of associated igneous rock composition and skarn sulfide mineral content. Mean silica content, in weight percent, for igneous rocks from Meinert (1983).

that contain average ore grades greater than 1 gram of gold per tonne and are usually associated with intense retrograde alteration. Gold-bearing skarns may contain significant amounts of numerous other commodities, including copper, lead, zinc, and iron and (or) they may have been mined in the past for these or other metals.

Examples

Copper skarns: Carr Fork, Utah; Meme, Haiti; Cananea, Sonora, Mexico.

Gold-bearing skarns: Fortitude, Nev.; McCoy, Nev.; Nickel Plate-Hedley, British Columbia, Canada; Red Dome, Australia.

Zinc-lead skarns: Groundhog, N.Mex.; Bismark, Chihuahua, Mexico.

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include porphyry copper (Model 17), iron skarn (Model 18d), polymetallic vein (Model 22c) and replacement (Model 19a), placer gold deposits (Model 39a), and distal disseminated silver-gold (Model 19c; Cox, 1992).

Potential environmental considerations

Surface and ground water associated with sulfide-mineral-rich tailings and waste piles or ponds may develop elevated concentrations of dissolved iron, aluminum, lead, copper, and zinc, especially if snowmelt and rain pond in tailings areas. At some inactive and abandoned historic mine workings where tailings are dispersed into streams, aquatic and plant communities may be impacted for as much as tens of km downstream by acidic conditions and (or) elevated metal concentrations. Sulfide mineral contents for these skarns are highly variable, and sulfide minerals may represent as much as 50 to 70 volume percent in parts of some deposits.

Exploration geophysics

Local magnetic highs may indicate skarn deposits with significant abundances of pyrrhotite and (or) magnetite. Precious metal skarns that contain abundant pyrite and quartz may lack this distinctive magnetic signature. In extremely weathered terranes, exposures of limonite, iron hydroxide, iron sulfate gossan, clay, or carbonate rock associated with these deposits may be identified by analyzing spectral features on Landsat Thematic Mapper reflectance imagery. Very low frequency electromagnetic and induced polarization surveys may be used to identify magnetite and associated disseminated sulfide bodies. Resistivity surveys can be used to model the distribution of alteration zones as indicated by ion concentrations of water saturated rocks. Because of density contrasts between alteration mineral assemblages and deposit host rocks, microgravity surveys may be used to delineate the distribution of skarn deposits.

References

Geology: Einaudi and others (1981), Cox (1986), Cox and Theodore (1986), and Theodore and others (1991).

Environmental signature: Ficklin and others (1992), Smith and others (1994), Apte and others (1995), and Salomons (1995).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Mosier (1986), Cox and Theodore (1986), Jones and Menzie (1986), and Theodore and others (1991) present deposit size ranges, expressed as percentiles of tonnages (million metric tonnes) for populations of N deposits:

Cu skarns (N=64):	0.03 (90th percentile)	0.56 (50th percentile)	9.2 (10th percentile)
Au skarns (N= 90):	0.0013 (90th percentile)	0.28 (50th percentile)	9.8 (10th percentile)
Zn-Pb skarns (N=34):	0.16 (90th percentile)	1.40 (50th percentile)	12 (10th percentile)

The 50th percentile value is the median deposit size for each population.

Host rocks

These deposits are in carbonate rocks, including limestone or marble, dolomite, and calcareous and dolomitic marble, pelite, argillite, shale, graywacke, and other clastic rocks. In terms of the bedrock type classification of Glass and others (1982), most host rocks for these deposit types are type IV; they are highly calcareous sedimentary rocks or metamorphosed calcareous sedimentary rocks that have extensive buffering capacity. Less common host rocks include chert, volcanic flows (dacite, andesite, or basalt) and volcanoclastic rocks, and metamorphic rocks such as slate or phyllite, quartzite, and amphibolite. These less common host rocks provide low to medium buffering capacity. At the Beal Mountain, Mont., gold deposit, gold-bearing rock is entirely in calcsilicate-bearing hornfels in clastic, quartz-rich host rocks. This deposit is atypical of skarns and may represent a distinct, but related type of disseminated gold deposit in contact metamorphosed rocks (Hastings and Harrold, 1988; Meinert, 1989).

Surrounding geologic terrane

These deposits are typically associated with contact zones around batholiths or plutons, including some relatively isolated small bodies, that intrude sedimentary strata. Zn-Pb skarns may lack spatial associations with intrusions.

Wall-rock alteration

Wall rock is altered to hornfels (quite widespread in places, and present throughout areas as large as 15 to 20 km²), marble, bleached limestone, and skarn zones; potassic, sericitic, argillic, propylitic alteration assemblages are developed and plutons may contain endoskarn. Silica and marble "fronts" (sharp boundaries between unreplaced rock and altered rock) may be present.

Nature of ore

Ore minerals may be present in massive, stratiform, vein, and (or) disseminated form; grain size is highly variable and ranges from fine to very coarse. Ore may be present in sulfide mineral zones, oxide zones, and in supergene, clay-rich oxidized zones. Sulfide minerals and gold generally are deposited during late, retrograde alteration within zones characterized by hydrous calcsilicates. Retrograde alteration may be best developed along faults cutting paragenetically earlier assemblages. Gold is commonly associated with a late pyrite + quartz assemblage (veins or disseminated). Note that many of these skarns contain zones that have been or could be mined for magnetite (see Fe skarn model, Hammarstrom and others, this volume). Total sulfide mineral content at the McCoy, Nev., gold skarn is low (<2 volume percent) and many sulfide minerals are oxidized. In contrast, at the Fortitude, Nev., gold skarn about 30 km to the north, high grade ore is sulfide mineral rich, and includes mostly pyrrhotite as well as lesser amounts of chalcopyrite, pyrite, arsenopyrite, and native bismuth.

Deposit trace element geochemistry

Cu skarns: Cu, Au, Ag in proximal zones; Pb, Zn, and Ag in distal zones; Co, As, Sb, Bi, and Mo anomalies in some deposits; calcic exoskarns are generally high in iron and sulfur; low in aluminum and manganese.

Au skarns: Au, Ag, Cu, As, Pb, and Zn; as well as Bi, Co, Sb, Te, Se, and Cd for some deposits.

Zn-Pb skarns: Zn, Pb, Mn, Cu, Co, Au, Ag, As, W, Sn, F, possibly Be; exoskarn, high in iron, sulfur, and manganese and low in aluminum.

Additional trace element data, including that pertaining to the geometry of their halos and distribution, for mineralized skarns are presented by Beus and Grigorian (1977). These data confirm the widespread natural distribution of many metals in these types of skarns.

Summary statistics for trace elements associated with selected Cu-Au skarn deposits are presented in tables 1 to 3. Ranges and means for elements (As, Cd, Se, Pb, Cr, and Hg) that are potentially harmful to aquatic biota are highly variable among deposits of the same type, and within different parts of single deposits (table 1A-C).

Table 1A. Data summary for drill core samples, provided by Battle Mountain Gold Company, from Fortitude, Nev. gold skarn deposit; tabulated by J.L. Doebrich. [Samples from border zone immediately surrounding Lower Fortitude ore zone (hosted by Pennsylvanian and Permian Antler Peak Limestone; Au <0.02 oz/t; N, number of samples)]

Element (unit)	N	Minimum	Maximum	Mean
Si (%)	185	5.5	36.8	15.8
K (%)	138	.002	3.2	.41
Al (%)	185	.60	4.4	1.7
Ca (%)	185	1.1	48.2	17.5
Mg (%)	185	.15	12.8	4.1
Mn (%)	104	.007	.88	.14
Ti (%)	185	.005	.49	.11
S (%)	185	.002	30.4	3.6
Fe (%)	138	.002	32.2	5.1
Rb (ppm)	96	1	241	24
Sr (ppm)	127	36	329	125
Ba (ppm)	138	3	3,830	272
Se (ppm)	128	1	124	11
As (ppm)	135	2	2,113	96
Sb (ppm)	114	1	47	11
Bi (ppm)	138	1	200	19
Mo (ppm)	101	1	68	5
Cu (ppm)	147	100	6,900	522
Pb (ppm)	26	3	7,300	138
Zn (ppm)	262	7	14,000	207
Ag (oz/t)	250	.01	9.4	.22
Au (oz/t)	210	.001	.02	.006

Table 1B. Data summary for drill core samples, provided by Battle Mountain Gold Company, from Fortitude, Nev. gold skarn deposit; tabulated by J.L. Doebrich. [Samples from Lower Fortitude ore zone (hosted by Pennsylvanian and Permian Antler Peak Limestone; Au ≥0.02 oz/t; N, number of samples); --, not detected]

Element (unit)	N	Minimum	Maximum	Mean
Si (%)	208	6.0	27.1	15.7
K (%)	173	.0003	4.3	.23
Al (%)	208	.7	14.3	1.8
Ca (%)	208	.21	22.1	7
Mg (%)	208	.29	13.0	2.9
Mn (%)	173	.05	.94	.19
Ti (%)	208	.0002	.47	.1
S (%)	208	.13	32.5	9.1
Fe (%)	173	.02	39.2	18.6
Rb (ppm)	173	--	85	7
Sr (ppm)	173	--	236	64
Ba (ppm)	173	--	1,289	135
Se (ppm)	173	--	169	15
As (ppm)	173	3	29,100	1,732
Sb (ppm)	173	--	47	7
Bi (ppm)	173	7	1,730	114
Mo (ppm)	130	--	19	4
Cu (ppm)	301	--	12,800	1,334
Pb (ppm)	301	8	7,400	261
Zn (ppm)	301	5	14,800	361
Ag (oz/t)	301	--	12.7	1.1
Au (oz/t)	301	.02	5.2	.36

Table 1C. Data summary for drill core samples, provided by Battle Mountain Gold Company, from Fortitude, Nev. gold skarn deposit; tabulated by J.L. Doebrich.

[Analyses from Upper Fortitude ore zone (hosted by Middle Pennsylvanian Battle Formation; Au <0.02 oz/t; N, number of samples)]

Element (unit)	N	Minimum	Maximum	Mean
Si (%)	109	17.9	40.3	26.8
K (%)	109	.01	6.1	2.4
Al (%)	109	1.2	13.8	4.2
Ca (%)	109	.003	5.9	1.2
Mg (%)	109	.01	8.8	2.9
Mn (%)	109	.01	.18	.05
Ti (%)	109	.11	.56	.29
S (%)	109	.09	17.1	5
Fe (%)	109	2.7	22.5	8.9
Rb (ppm)	101	6	253	98
Sr (ppm)	94	31	134	65
Ba (ppm)	109	50	4,127	1,784
Se (ppm)	109	3	117	18
As (ppm)	107	2	19,700	633
Sb (ppm)	95	1	74	7
Bi (ppm)	107	2	332	63
Cu (ppm)	610	100	49,800	1,704
Pb (ppm)	614	3	8,780	147
Zn (ppm)	614	3	7,400	274
Ag (oz/t)	614	.01	9.7	.35
Au (oz/t)	614	.02	.48	.06

Table 2. Summary ranges of trace element data for some precious metal-enriched skarns in British Columbia.

[Data from Ettlinger and Ray (1989, Appendix 7). Data represent 76 samples of skarn, endoskarn, and associated rocks from skarn deposits in Banks Island, Oka, Benson Lake, Nanaimo Lakes, Dividend-Lakeview, Texada Island, and Greenwood mining districts. Analyses by atomic absorption spectrometry]

Element	Detection limit	Minimum	Maximum
Au (ppb)	20	<20	103,000
Ag (ppm)	.5	<.5	200
Cu (ppm)	10	7	193,000
Pb (ppm)	5	<5	1,500
Zn (ppm)	5	8	29,000
Co (ppm)	3	<3	17,000
Mo (ppm)	10	<10	248
As (ppm)	3 to 10	<1	445,000
Bi (ppm)	3	<3	32,000

The Copper Canyon area, Nev., (fig. 2) contains copper, gold, lead-zinc skarns whose geochemical signatures are characteristic of those associated with these deposit types. Skarn deposits in the central part of the map area (fig. 2A) were unexposed prior to mining. Broad areas of outcrop had elevated abundances of copper (>700 ppm) prior to large-scale mining activity (fig. 2B). Concentrations of lead, mercury, arsenic, and cadmium are controlled strongly

Table 3. Summary ranges of geochemical data for trace elements in fresh and variably altered rocks from northern part of New World Cu-Ag-Au district, Mont.

[Data, in ppm unless otherwise noted, from Johnson (1991, Table F-1). Samples include drill core, outcrops, and ore dumps. Fire assay and atomic absorption methods. Mean based on number of samples in which element was detected at concentrations above detection limits; --, not detected]

Element	Detection Limit	Number of Samples	Minimum	Maximum	Mean
Au	0.005	108	0.006	176	3
Cu	1	110	--	135,300	6,366
Ag	.2	105	--	300	14
Te	.2	102	--	76	6
Bi	1	85	2	1,505	46
As	5	78	<5	289	69
Pb	2	96	3	132,000	1,610
Zn	1	111	4	132,700	1,669
Ni	1	102	1	152	34
Co	1	93	1	275	22
Mo	1	94	1	62	7
Cr	1	111	2	674	105
Se	5	43	5	420	31
Hg(ppb)	5	108	<5	1,900	58
Sb	5	43	.6	580	25
W	10	46	5	316	41
Ba	20	73	30	2,200	645
Mn	1	111	--	4,670	848
Ti	.5	38	.1	2.3	.78

by surface distribution of pre- and syn-mineralization faults that acted as conduits for mineralizing fluids. Most rocks with anomalous cadmium abundances are north of the outer limit of the dispersed iron sulfide halo that surrounds almost all of the large disseminated deposits (fig. 2F). In addition, mercury, and to a lesser degree tin abundances, appear to be sharply zoned relative to some of the most intensely mineralized skarns (B.B. Kotlyar, unpub. data, 1995). Similar relations characterize soil geochemistry around the McCoy deposit, Nev. (fig. 3). Summary statistics for the Fortitude, Nev., gold-rich skarn in the Copper Canyon area are shown in table 1.

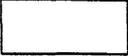
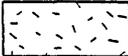
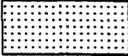
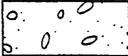
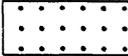
Summary ranges of trace element geochemical data for fresh and variably altered rocks from the northern part of the New World, Mont., copper-gold-silver district (Johnson, 1991), which includes the historic McLaren Mine are listed in table 3. In addition, Van Gosen (1994) analyzed 100 samples from the Homestake breccia deposit, one of five copper-gold-silver skarn and replacement deposits recently delineated by exploration in the New World district, and located less than 1 km southeast of the McLaren Mine. Van Gosen (1994) demonstrated that the Homestake orebodies are best categorized as gold-bearing skarns in the upper parts of a porphyry copper system. By comparing metal concentrations in samples of ore (Au >3,125 ppb), sub-ore (3 ppb < Au <3125 ppb), and background rock (Au <3 ppb), Van Gosen (1994) computed enrichment-depletion ratios for 24 selected metals in the Homestake deposits. Relative to background, the following elements are enriched in ore and sub-ore: Au, Ag, Cu, Mg, As, Bi, Co, Cr, Ga, Mn, Nb, Ni, Pb, and Zn. Barium, lithium, strontium, and zirconium are depleted in ore and sub-ore samples relative to background samples, whereas aluminum, potassium, sodium, titanium, and vanadium are depleted in ore samples but enriched or unchanged relative to background in sub-ore samples.

Ore and gangue mineralogy and zonation

Skarn deposits exhibit temporal and spatial zoning that reflects various stages of skarn development. Early formed prograde mineral assemblages are variably overprinted and crosscut by retrograde assemblages. Initial metamorphism forms marble and hornfels, which may be present in extensive surrounding halos. Subsequent metasomatism forms high-temperature, anhydrous calcsilicate assemblages that may be overprinted or cut by lower temperature hydrous assemblages including sulfide minerals (mainly pyrite) deposited under conditions of increased sulfur concentrations.

Cu skarns: Prograde- Pyroxene (diopside-hedenbergite), garnet (andradite-grossular), wollastonite.
Retrograde- Actinolite, chlorite, clay, epidote.
Ore- Chalcopyrite, pyrite, hematite, magnetite, sphalerite, galena, arsenopyrite; less common, bornite, pyrrhotite, molybdenite, tennantite, bismuthinite, enargite, cobaltite, and tetrahedrite.

EXPLANATION

-  Younger alluvium and conglomerate deposits (Quaternary)
-  Altered granodiorite and quartz diorite (Tertiary)
-  Havallah sequence (Permian, Pennsylvanian, and Missisipian) -- In this area includes only lithotectonic unit 1 of Murchey (1990) (Permian and Pennsylvanian); argillite, shale, and chert
-  Antler sequence of Roberts (Permian and Pemsylvanian) -- Includes conglomerate of Middle Pennsylvanian Battle Formation, limestone of Pennsylvanian and Permian Antler Peak Limestone, and sandstone and conglomerate of Permian Edna Mountain Formation
-  Scott Canyon Formation (Devonian) -- Chert, shale, argillite
-  Harmony Formation (Upper Cambrian)-- Mostly feldspathic sandstone

-  Geological contacts
-  High angle fault -- bar and ball on side of down-dropped block
-  Thrust fault -- sawteeth on upper plate
-  Outer limit of pyritized rocks, hachures on side of pyritized rock
-  Projection to the surface of outer limit of large disseminated deposits
-  Small vein deposits and occurrences

Projection to the surface in *B-F* of outer limit of :

-  Cu, Au, Ag altered porphyry deposits
-  Cu, Au, Ag skarn deposits, unexposed prior to mining, sulfide
-  Au, Ag (Pb, Zn, Cu) skarn deposits, exposed prior to mining, sulfide
-  Au, Ag (Cu, Pb, Zn) skarn deposits, oxidized, exposed prior to mining
-  Trend of major drainages showing stream-flow direction

Concentrations of select metals in 2,927 rock samples
(in parts per million; N.A., not applicable)

	Copper	Lead	Mercury	Arsenic	Cadmium
	<50	<10	<0.02	<200	<20
	50-150	10-70	0.02-0.2	N.A.	N.A.
	200-700	100-700	0.2-1	200-700	20-50
	>700	>700	>1	>1000	>70

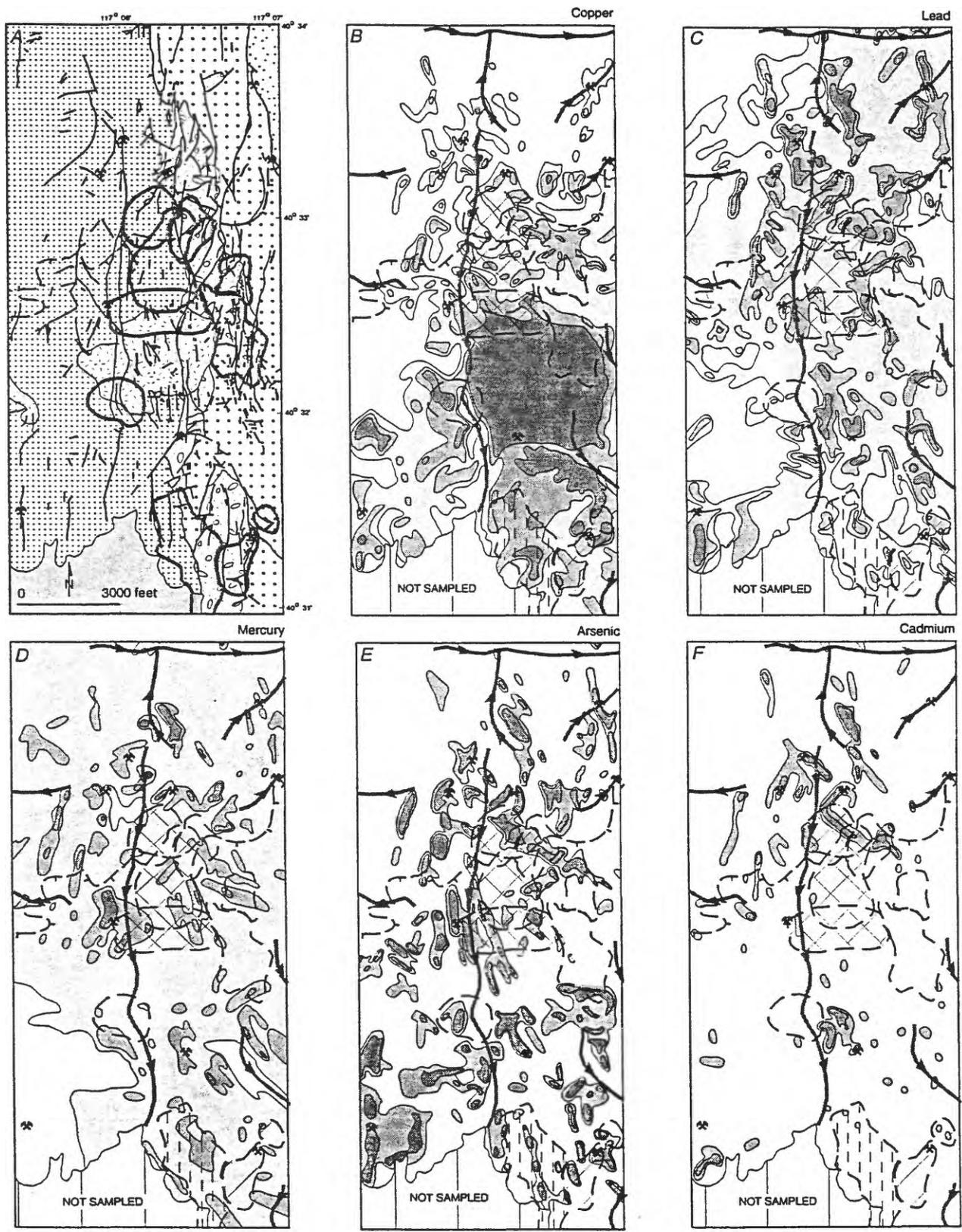
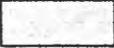
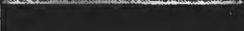


Figure 2. Maps showing A, geology; and contoured distributions of B, copper; C, lead; D, mercury; E, arsenic; and F, cadmium in 2,924 rock samples at Copper Canyon, Battle Mountain district, Nev. Geochemical data from Theodore (1969), geology modified from Theodore and Blake (1975), and surface projections of ore deposits from Doebrich and others (1995).

EXPLANATION

-  Alluvium (Quaternary)
-  Felsite porphyry (Tertiary)
-  Granodiorite (Oligocene) -- Brown stock, 38-39 Ma
- Cane Spring Formation (Upper Triassic) -- In this area includes:
-  Limestone Member  Clastic Member
-  Osobb Formation (Upper Triassic)
-  Augusta Mountain Formation (Middle and Upper Triassic)
-- In this area includes Smelser Pass Member
-  Skarn, marble, and jasperoid  Open pit
-  Contacts  High angle fault

Concentrations of select metals in soil samples
(in parts per million; --, not detected)

	Gold	Copper	Arsenic
	<0.1	<50	<5
	0.1-0.2	50-100	5-10
	0.2-0.3	100-200	10-15
	0.3-0.4	200-300	15-20
	>0.4	>300	--

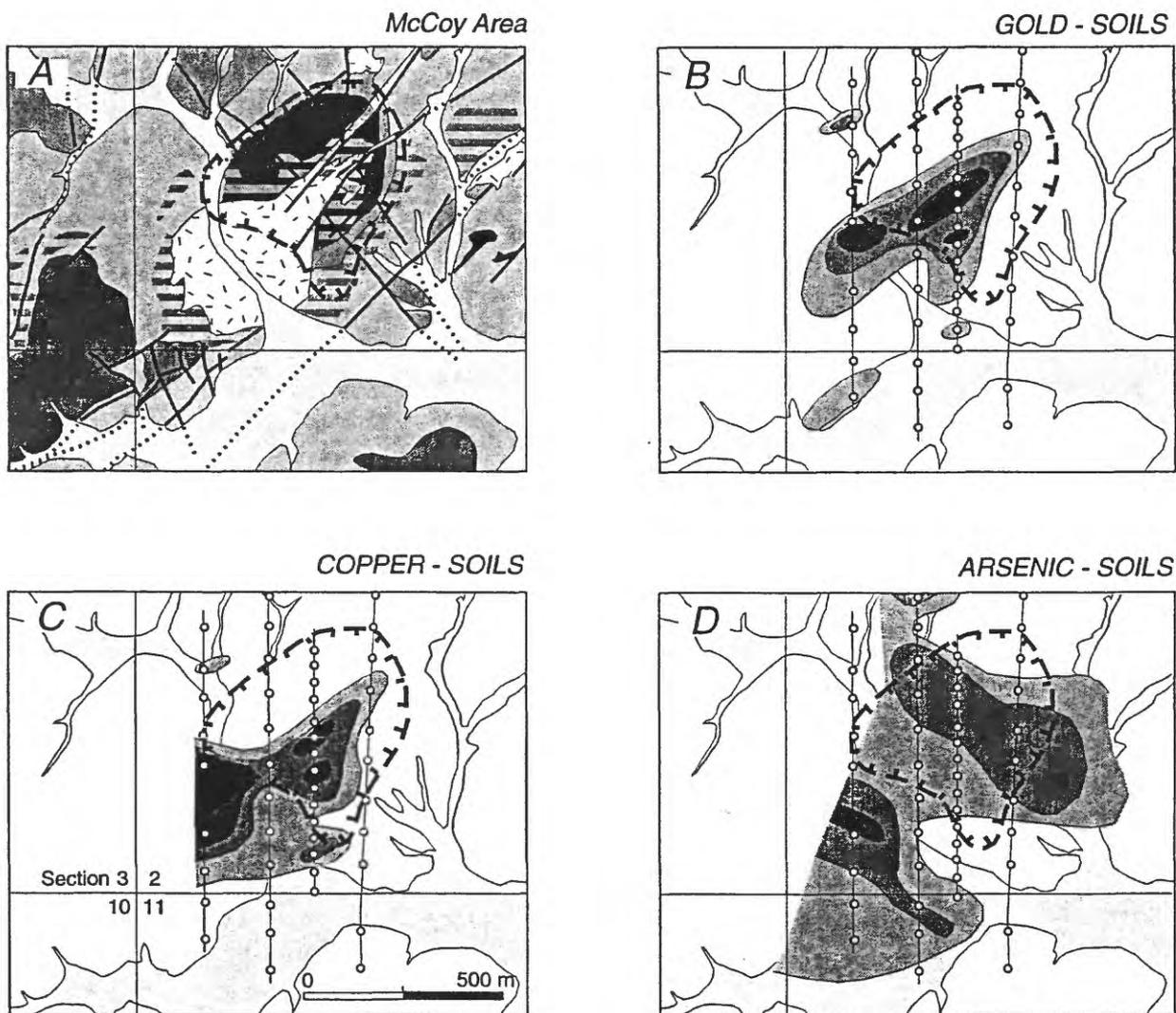


Figure 3. Maps showing *A*, geology, and contoured distributions of *B*, gold; *C*, copper; *D*, arsenic in soil at McCoy, Nev. gold skarn deposits. Geochemical data from Echo Bay Corporation (written commun., 1995); geology from Emmons and Eng (1995).

- Au-bearing skarns:** Prograde- Garnet (andradite-grossular), pyroxene (diopside-hedenbergite), idocrase, wollastonite. Retrograde- Epidote, amphibole, chlorite, prehnite, scapolite, boron minerals, potassium feldspar, clay, siderite.
Ore- Gold (electrum), pyrite, pyrrhotite, chalcopyrite, arsenopyrite, magnetite, hematite (specularite), sphalerite, galena, bismuthinite or native bismuth, hedleyite, telluride minerals, molybdenite, and scheelite; gold is present as native gold or electrum associated with pyrrhotite, chalcopyrite, or with quartz-pyrite assemblages.
- Zn-Pb skarns:** Prograde- Pyroxene (hedenbergite-johannsenite), garnet (andradite-spessartine), bustamite, rhodonite. Retrograde- Actinolite (Mn-rich), ilvaite, chlorite, dannemorite, rhodochrosite, epidote.
Ore- Sphalerite, galena, pyrrhotite, pyrite, magnetite, chalcopyrite, arsenopyrite; manganese-rich silicate and carbonate minerals are a distinctive characteristic of Zn-Pb skarn deposits.

Mineral characteristics

Ore may be present in sulfide-mineral-rich, massive lenses or pods or it may be disseminated. At the Nickel Plate mine in Canada, <25-micron-diameter grains of native gold associated with hedleyite are adjacent to arsenopyrite and gersdorffite. In other parts of the same deposit, electrum is concentrated in microfractures in and around chalcopyrite, pyrrhotite, sphalerite, and bismuth (Ettlinger and Ray, 1989). In contrast, gold at the McCoy, Nev., skarn is spatially and paragenetically associated with late-stage pyrite and forms 20- to 100-micron-diameter grains

bordering pyrite cubes. Mineral characteristics in skarns are likely to vary considerably within a single deposit due to the zoned nature of skarns and replacement of early-formed minerals by later mineral assemblages. In zinc-lead skarns, ore commonly forms massive pods of pyrrhotite, sphalerite, galena, and chalcopyrite in pyroxene zones.

Secondary mineralogy

Gossans develop over sulfide-mineral-rich parts of skarn deposits and may concentrate metals. Manganese oxide rich gossans are associated with zinc-lead skarns. Supergene alteration (oxidation) leads to formation of clays, hematite and goethite (after pyrite and other sulfide minerals), and secondary copper minerals (after chalcopyrite). Gold-rich skarn at the McCoy, Nev., deposit is highly oxidized and argillized to as much as 245 m below the present surface (Brooks and others, 1991). Minerals in these argillized zones include a variety of clays (montmorillonite, nontronite, smectite, and illite), manganese oxide minerals, supergene copper oxide minerals, claudetite (As_2O_3), willemite (Zn_2SiO_4), marcasite, and hydrated iron oxide minerals. At the Red Dome Au skarn deposit in North Queensland, Australia, high-grade gold ore is concentrated in highly oxidized karst-collapse breccia which formed during post-mineralization uplift and erosion; oxidation of primary tellurium-rich hypogene sulfide ore promoted karst formation and concentration of free gold (Torrey and others, 1986). Mineralogy and zoning that develops during supergene alteration of zinc-lead-silver sulfide ore in carbonate rocks depends on local Eh and pH conditions, permeability, and relative activities of carbonate species and sulfate ions in leaching ground water (Sangameshwar and Barnes, 1983). For example, cerussite is the first lead mineral to precipitate where dissolved carbonate is more abundant than sulfate, but anglesite precipitates if the situation is reversed. Supergene minerals associated with copper-lead-zinc-silver ore include azurite, malachite, smithsonite, cerargyrite as well as cerussite, anglesite, manganese minerals (pyrolusite, groutite), goethite and sulfide mineral products from bacterial reduction.

Topography, physiography

Skarn deposits in the western conterminous United States typically are present in mountainous areas, but can be present in a variety of settings; some are buried in fault blocks under Tertiary or Quaternary basin fill. Skarns also may be present in roof pendants in plutons, as well as at contacts with plutons. These types of skarns are in continental margin, syn- to late-orogenic tectonic settings such as those exposed in British Columbia, Peru, Japan, and the western Cordillera of the United States and Mexico.

Hydrology

In some deposits, shear zones and faults are important structural controls for channeling hydrothermal fluids and subsequent mineralization. In other deposits, lithologic contacts serve as fluid conduits. Post-mineralization faults may also channel fluids. At Minera Bismark, a zinc-lead skarn deposit in northern Mexico, water flows continuously along a major post-mineralization fault, as well as along other faults and fractures in granitic rock, necessitating a pumping system to dewater the orebody (Mining Magazine, 1994). Ferricrete deposits represent iron remobilized from weathered sulfide minerals by surface and subsurface water and indicate locations of former springs or drainage seepages. Manganese or iron bog deposits may provide clues to paleohydrology in the vicinity of base and precious metal skarn deposits. Faults at Copper Canyon, Nev., are known to have channeled ground water for several km during periods of enhanced ground-water availability.

Mining and milling methods

These deposits have been exploited by open pit and underground mining methods. Copper-gold ore is milled primarily by gravity and flotation methods. Copper is usually recovered by flotation. Gold is commonly recovered by cyanide leaching of crushed ore using carbon adsorption, carbon stripping at elevated temperatures and pressures, electrowinning and refining to produce dore bullion. Crushed ore may be agglomerated with cement and lime before leaching to stabilize it and promote thorough leaching. A new pyrite flotation process is available as a substitute for cyanide processing of pyrite-rich gold ore to produce tailings that have negligible acid generation potential. Resulting gold-rich pyrite concentrates are dewatered and shipped to smelters for refining. Differential flotation and separation processes are used to recover metals from complex polymetallic ore (for example, the zinc-lead skarn at Minera Bismark, Mexico) after crushing and milling to produce concentrates for shipment to smelters.

ENVIRONMENTAL SIGNATURES

Surface disturbance

Surface disturbance associated with mining these deposits is variable. Historic deposits were typically mined by hand

Table 4A. Summary of water analyses associated with historic mining of the McLaren sulfide mineral-rich Cu-Au-Ag skarn deposit in the New World district, Mont. Surface water stations and ground water observation wells.

[The McLaren open pit mine and mill operated from 1934 to 1953. Data compiled from reports cited in SCS Engineers, 1984; N, number of observations; flow, in cubic feet per second; SC, specific conductance in micromhos/cm; other measurements in mg/l. Samples were collected and analyzed in 1973 to 1975 and in 1983. N.d., not determined]

Parameter measured	Ground water analyses			Surface water analyses		
	N	Minimum	Maximum	N	Minimum	Maximum
Flow	N.d.	N.d.	N.d.	21	0.06	293
pH	47	2.22	8.03	29	3.69	8.17
SC	47	103	26,300	29	104	1,480
Acidity	16	123	13,200	9	14.2	176
Alkalinity	42	0	469	24	0	118
SO ₄	42	1.6	49,900	25	7.2	854
Si	41	2.2	62	25	5.6	29.6
Fe ¹	20	<0.02	3,660	10	0.09	143
Fe ²	42	<0.03	20,600	24	<0.03	198
Al	35	<0.1	21.4	21	<0.01	4.56
Pb	24	<0.02	0.74	19	<0.003	0.07
Cu	23	<0.01	15.93	21	<0.01	0.5
Zn	22	<0.01	2.69	20	<0.005	0.3
Cd	23	<0.02	0.1	19	<0.001	0.02

¹ Total recoverable iron

² Total dissolved iron

Table 4B. Summary of water analyses associated with historic mining of the McLaren sulfide mineral-rich Cu-Au-Ag skarn deposit in the New World district, Mont. Total recoverable metals in mine and mill site drains; measured in September, 1979. Data in mg/l. [--, not detected]

Parameter measured	Mine site	Mill site
pH	4.5	5.0
Cu	3.56	--
Zn	0.14	0.12
Fe	33.7	17.2
Mn	1.01	2.94

in underground workings. Multiple adits, pits, and tailings piles are commonly present at inactive and abandoned workings because skarn deposits were often explored or worked at different sites, and at different times in the past, along limestone-pluton contacts. Placer gold workings are downstream from many gold-bearing skarn deposits. Some placer gold workings have affected areas of as much as 5 km².

Drainage signatures

Analogies with mine drainage compositions for polymetallic replacement deposits characterized by pyrite + chalcopyrite + sphalerite + galena veins or replacements in carbonate-rich host rocks (for example, Leadville, Colo.), indicate that mine drainages are likely to exhibit near-neutral pH ranges, carry moderate concentrations of dissolved metals (10 to 100 mg/l total Zn+Cu+Cd+Pb+Co+Ni), but may contain elevated (as much as 100,000 mg/l) amounts of zinc. Dissolved aluminum and iron concentrations are both likely to about 100 mg/l, but can be much less (Smith and others, 1994). Parts of deposits that are not in contact with carbonate rocks may cause associated drainages to be more acidic and metal rich. See tables 4 and 5 for examples of compositions of surface and ground

Table 5. Chemical analysis of a water sample from the Cananea Cu skarn deposit, 275 m level, Sonora, Mexico; all data in mg/l.

[Data from White and others (1963, Table 24).

Water affected by oxidation of disseminated sulfide minerals]

SiO ₂	56
Al	22
Fe ²⁺	524
Mn	153
Cu	60
Zn	252
Ca	753
Mg	86
Na + K	198
SO ₄	4,460
Cl	22

water associated with selected sulfide-mineral-rich copper skarn deposits. These data indicate total recoverable metals and, therefore, provide no information concerning dissolved versus suspended metals or metal speciation. Seasonal fluctuations affect flow and pH in some climates, especially where snow melt affects surface water during summer months (fig. 4). Various parameters of surface and ground water from monitoring sites in the New World, Mont., copper-silver-gold district are plotted in figure 5. These sites are on, or immediately adjacent (within 100 m) to, an 87,000 km³ tailings pile removed from the mine site. These data (table 4A) for water samples collected in the 1970s and early 1980s (SCS Engineers, 1984), reflect signatures that developed from mine tailings at a mill site for ore from the McLaren mine, a skarn that was worked as an open pit mine from 1934 to 1953. At the time of the analyses, a stream flowed directly over part of the tailings pile. The stream ran red and was impacted for about 16 km. The stream contained no fish and was characterized by reduced benthic organism populations mainly due to high dissolved iron and relatively high aluminum concentrations. Rock geochemical data (table 3) from the New World district include samples from in and around the historic McLaren mine. Water data from mine and mill site drainages are cited in table 4B. Many surface and ground water samples have near-neutral pH values (6 to 8). Specific conductance (a measure of dissolved solid content), iron, and to a lesser extent aluminum, all increase dramatically with decreasing pH (fig. 5). Sulfate concentration increases with increasing specific conductance (fig. 5) in both surface and ground water. However, ground water has much higher sulfate concentrations and specific conductances than surface water for the same pH ranges (note the difference in scale on fig. 5). These same data are plotted on a modified Ficklin diagram to show base metal abundance ranges as a function of pH (fig. 6). Note that the original Ficklin diagram (Ficklin and others, 1992) was devised to show the variations in aqueous (not total) base metal concentrations for systematically sampled water draining diverse ore deposit types in Colorado and included nickel and cobalt. Nevertheless, the New World water data mainly plot (fig. 6) in the near-neutral to acid, low to high metal fields and are much less acidic than water that drains many other deposit types. As Ficklin and others (1992) noted, the ability of carbonate-hosted deposits to generate metal-rich water appears to be a function of sulfide mineral content. The unusually high pyrite content of skarn ore at New World, along with the unusual situation of stream flow directly over tailings, led to some relatively high metal abundances in water on a local scale. However, iron and aluminum, not base metals, were cited as the primary pollutants during a U.S. Environmental Protection Agency (EPA) investigation. Many skarns in Nevada, however, are in semi-arid to arid climatic environments where annual rates of evaporation exceed annual rainfall and commonly most stream flow is intermittent.

A variety of samples, including stream sediment, heavy-mineral concentrates, soil, pond and spring mud, and iron-rich stream and mine adit flocculent precipitates, were collected in September, 1993, as part of a geochemical baseline study of the New World, Mont., district and adjacent areas (R.R. Carlson and G.K. Lee, unpub. data, 1995). In addition, *in-situ* pH and conductivity readings of water in streams, ponds, springs, seeps, and mine

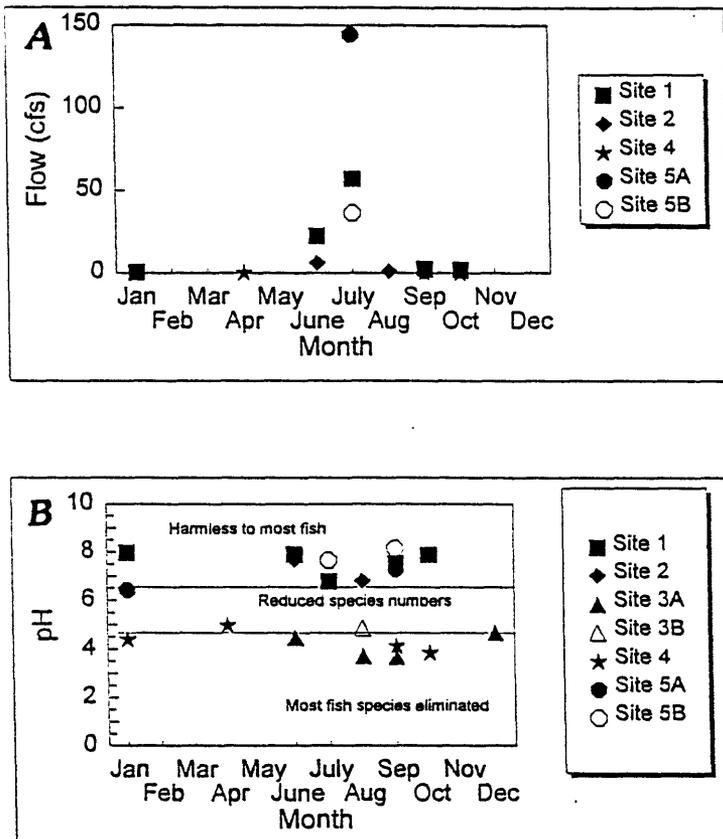


Figure 4. Seasonal variations in A, stream flow and B, pH for surface water from monitoring sites adjacent to a tailings pile at an historic mill site along Soda Butte Creek in the New World, Mont., district. These data reflect impacts caused by a tailings pile failure rather than drainage from a mine. The tailings were removed from the McLaren copper-gold-silver mine and placed at the mill site several km south of the mine. Two data sets, which represent sampling in 1974 (a) and 1975 (b), are plotted for sites 3 and 5. Dashed lines on B separate pH ranges in terms of generalized effects of pH on aquatic ecosystems (based on Potter and others, 1982). Note that the average pH value for precipitation in this area is 5.3. Water data from SCS Engineers (1984).

adits and open pits were made. Figure 7 is a preliminary contour map of pH ranges generated from the unpublished data and augmented by data from the National Uranium Resources Evaluation (Broxton, 1979). Areas characterized by high acidity (pH < 5) represent water in a variety of settings. pH values in the area at the southeast end of Henderson Mtn. represent standing water in an inactive open-pit mine and low-volume seeps down hill from the pit. pH values for the area in the headwaters of the Stillwater River represent water draining recontoured mine waste rock. Most of the low pH values in the upper reaches of Fisher Creek represent discharge from abandoned adits; the remainder of these low pH values represent spring water. In all cases, highly acidic water appears to be ameliorated to near-neutral pH, probably as a consequence of buffering by water draining limestone and calc-alkaline intrusive rocks of the New World area, within 1000 meters of source areas.

In natural water, free metal ions such as Cu^{2+} are the most bioavailable and most toxic aqueous species; however, complexing with dissolved organic matter greatly reduces bioavailability.

Metal mobility from solid mine wastes

Oxide zone mine waste from skarn deposits may pass environmental monitoring tests for static acid generation potential and mobilization, whereas sulfide mineral zone wastes from the same deposit may fail such tests.

The mobility of metals from solid mine waste (tailings) varies as a function of pH, Eh, and the composition of tailings. Pathways for metal release from tailings include structural failure of tailings (for example, during a flood), direct discharge of tailings into surface water, dust, concentration in plants, erosion, and leaching into ground water (Andrews, 1975). The presence of sulfide minerals, especially pyrite, in tailings exposed to oxidation promotes development of acid mine drainage and concomitant metal mobility if carbonate mineral content and dissolution rates in tailings are insufficient to neutralize sulfide mineral oxidation (Ripley and others, 1995). Although carbonate rock

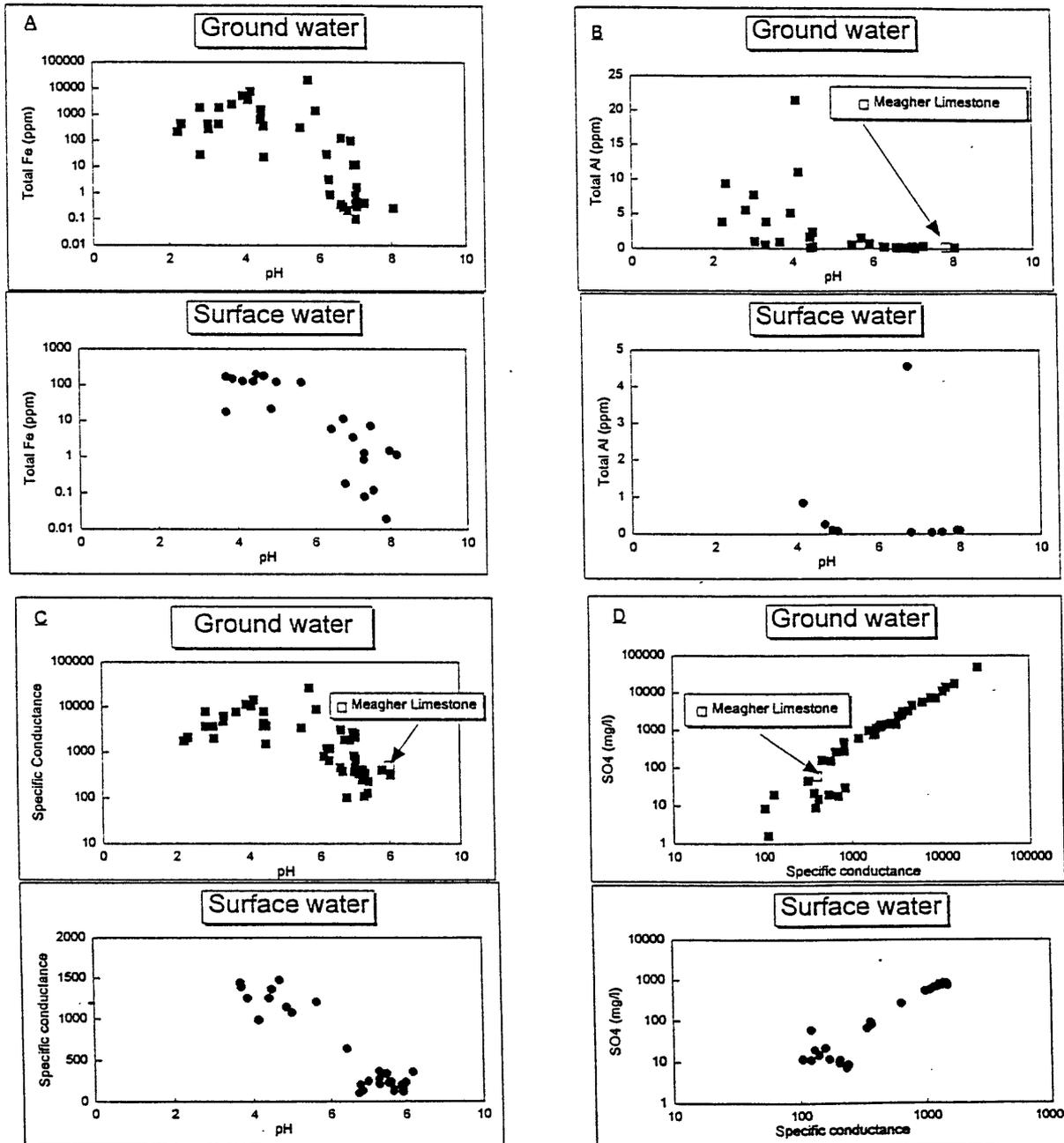


Figure 5. Plots showing A, relationships between pH and iron abundances; B, pH and aluminum abundances; C, specific conductance and pH; and D, between sulfate abundances and specific conductance for ground (squares) and surface (circles) water in the New World district, Mont. Water data from SCS Engineers (1984). Ground water chemistry for Middle Cambrian Meagher Limestone (at Ennis, about 130 km north-northwest of the New World district) reported by White and others (1963, table 6) is shown for reference (open square). The Meagher Limestone is the most important host rock for skarn deposits in the New World district (Johnson, 1991).

is commonly present in skarn deposits, waste rock may include less reactive gangue minerals, including silicate minerals, and tailings may have highly variable acid-buffering capacity. Andrews (1975) reports typical abundances for a number of metals, including 6 to 38 ppm lead, 10 to 65 ppm zinc, and 1 to 35 ppm copper, in tailings associated with a number of deposit types.

Metals released from weathered primary (hypogene sulfide ore) and secondary (supergene oxide and sulfide) minerals in tailings at the Kelley zinc-lead skarn deposit in the Magdalena, New Mex., district are fixed by precipitation of tertiary minerals and by ion exchange into phyllosilicate minerals on grain surfaces and along

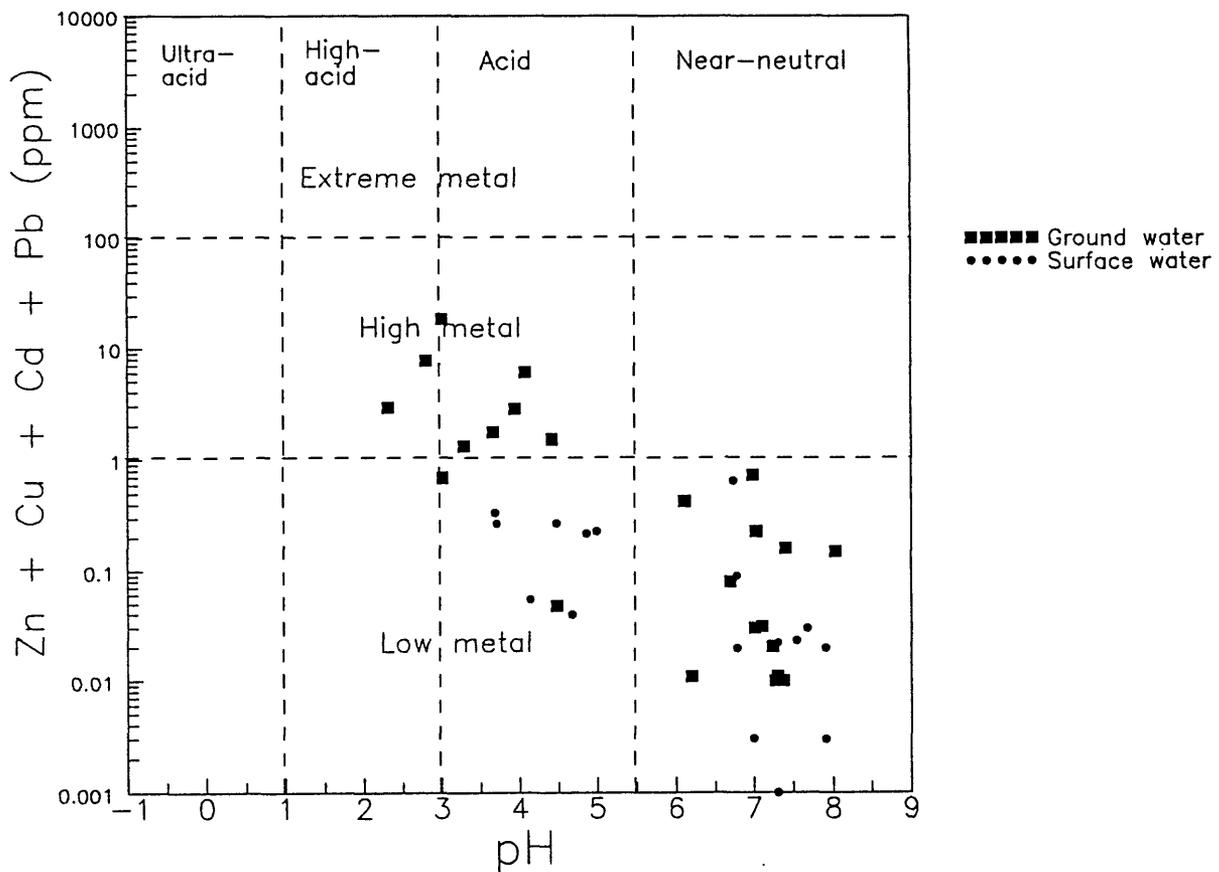


Figure 6. Variations in base metal concentrations (Zn+Cu+Cd+Pb) versus ground and surface water pH, New World district, Mont. Water data from SCS Engineers (1984). Classification scheme modified from Ficklin and others (1992).

fractures. Primary sulfide minerals persist as the main source of metals in sediments derived from tailings; these sediments contain as much as 1.9 weight percent lead, 6.2 weight percent zinc, and 279 ppm cadmium (Larocque and others, 1995).

Soil, sediment signatures prior to mining

Soil sampling has been proven useful as an exploration tool for delineating exploration targets for gold-bearing skarn systems. Hastings and Harrold (1988, fig. 7) showed that ranges for selected trace elements in rocks and soil at the Beal gold-skarn(?) deposit generally overlap. Arithmetic means for trace element concentrations in soil samples are similar to means for rock samples with the exception of gold (0.05 ppm in soil, 1 ppm in rock). Means for both soil and rock for arsenic, copper, and zinc at the Beal deposit are between 10 and 100 ppm; soil appears to be slightly enriched in arsenic and zinc relative to rocks.

The geology of the McCoy gold-silver-copper skarn deposit is shown in figure 3, along with contoured distributions of a number of metals (copper, arsenic, and gold) in soil samples. The operations at Cove, Nev., which are part of the mineralized system at McCoy, were the leading producer of silver in Nevada in 1994. The data illustrate the pre-mining distribution of metals, that is, background (natural concentrations of elements in natural materials that exclude human influence) geochemistry for soil in the area (fig. 3). These data were collected during exploration for the present McCoy mine, prior to large-scale mining (figure 3 provided by Echo Bay Minerals, written commun., 1995). Soil in the general area of the McCoy, Nev., gold skarn deposit includes as much as 15 to 20 ppm arsenic and as much as 200 to 300 ppm copper (fig. 3C-D). At McCoy, an area as much as 750 m wide contained soil with more than 5 ppm arsenic prior to large-scale mining. Analyses of the minus-80-mesh fraction of 140 soil samples in the general area of the copper-gold-silver West orebody, Copper Canyon, Nev., reveal that the soil is alkaline (pH typically 9.0 to 9.6). Calcite was present in about one-third of the samples (Theodore and Blake, 1978). Contents of silver, arsenic, gold, copper, lead, and mercury in soil above skarn are generally anomalous. Median values are: 3 ppm silver, 0.15 ppm gold, 150 ppm copper, 50 ppm lead, and 0.7 ppm mercury. Mercury contents in the soil appear to be higher along some traverses just outside or beyond the surface projection of underlying ore. Arsenic is >160 ppm in some soil samples. These are natural concentrations, uncontaminated

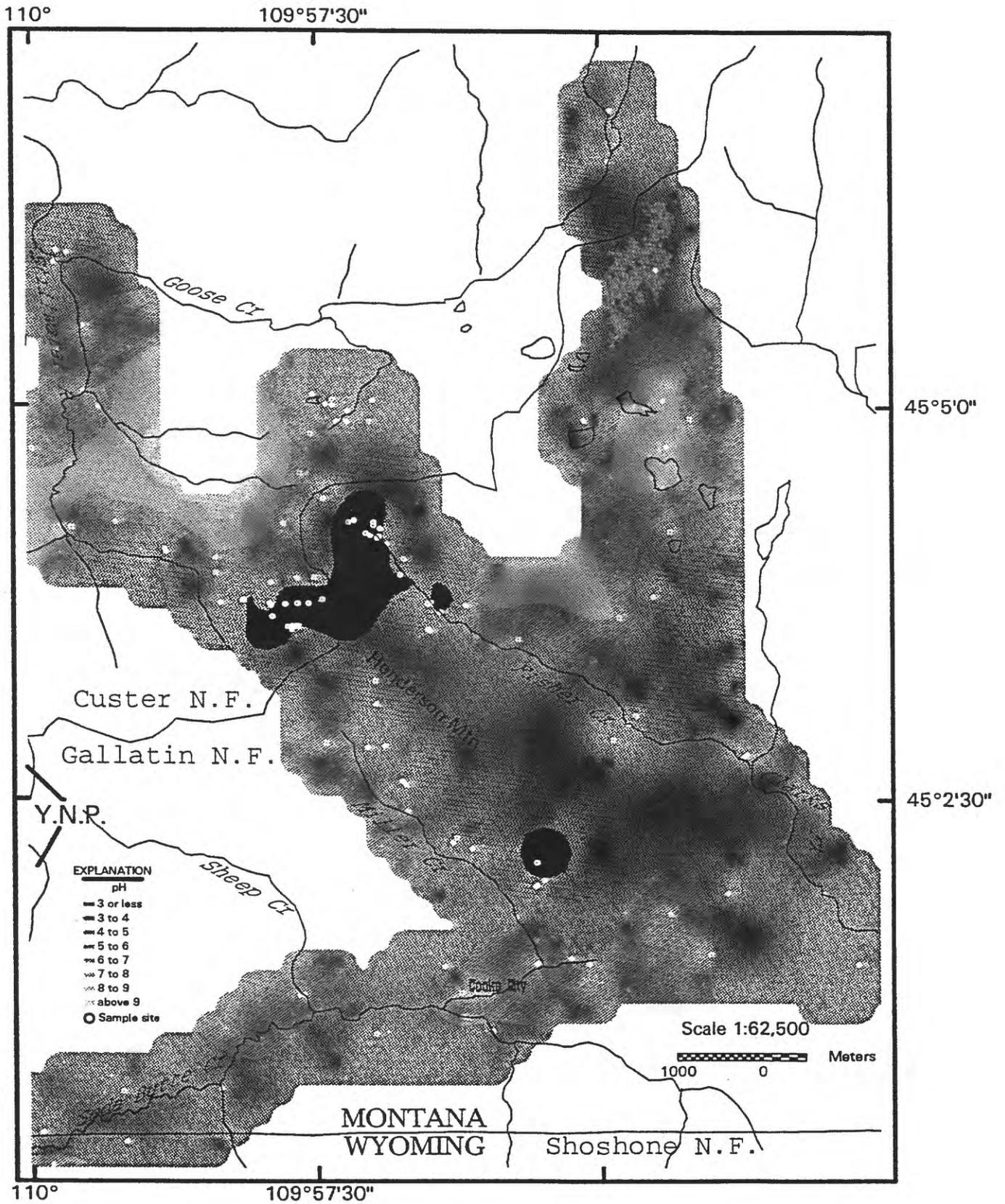


Figure 7. Contoured pH ranges in surface and ground water of the New World, Mont., district (R.R. Carlson and G.K. Lee, unpub. data, 1995).

by mining activities.

The contrast between arsenic abundances in soil at the McCoy (15 to 20 ppm) and West (>160 ppm) orebodies shows that similar deposits in similar geologic and climatic conditions can have distinctly different geochemical signatures. Although these two deposits formed in different carbonate strata, in different tectonic blocks, both are copper-gold-silver skarn deposits associated with 39 Ma granitoid intrusions in north-central Nevada and both deposits are in arid-climate settings (Bailey and others, 1994) where precipitation averages 100 to 300 mm and elevations range from 1,200 to 3,000 m.

Potential environmental concerns associated with mineral processing

Poor site selection for tailings piles or mineral processing operations, leach pads, and settling ponds can lead to chemical (acid or metal loading) or physical (increased turbidity or sedimentation) degradation of surface and ground water and soil. Potential problems associated with cyanide heap leach operations include leach solution overflow during heavy rains and rapid snowmelt, liner failures in pads or ponds, and inadequate neutralization of cyanide solutions and cyanide-treated heap-leach pads at mine closure (Norman and Raforth, 1995). Free cyanide degrades naturally by volatilization, especially at elevated temperatures with ultraviolet radiation in solutions enriched in dissolved oxygen or CO₂. These favorable conditions may not obtain in areas where winters are long and severe, or in ground water. In such cases, heap detoxification may be accomplished by a variety of chemical or biological processes.

Smelter signatures

Copper smelters release SO₂ gas and represent the largest single source of arsenic emission from industrial processing of non-ferrous metals (Loebenstein, 1994). Flue dusts from copper smelters commonly contain lead, zinc, arsenic, and other metals. Copper concentrations in air near copper smelters may be elevated from normal abundances of a few to 200 ng/m³ to abundances on the order of 5,000 ng/m³. Smelters (copper, zinc, and lead) in the United States have been regulated for emissions and metal effluents since the mid 1970s.

Climate effects on environmental signatures

The effects of various climatic regimes on the geoenvironmental signature specific these deposits are not known. However, in most cases the intensity of environmental impact associated with sulfide-bearing mineral deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell.

Geoenvironmental geophysics

Multispectral remote imaging over sparsely vegetated areas can help identify oxidized mine tailings. Ongoing heat evolution associated with sulfide mineral oxidation can be identified by airborne infrared surveys. Electromagnetic or direct current resistivity surveys can be used to identify and track metal-contaminated ground water flowing from tailings or mine shafts. Self potential, shallow seismic, and electrical surveys can be combined to provide information on the thickness, structure, and possibly the presence of oxidation-reduction centers associated with tailings and mine waste.

Examples of case studies of the environmental impact of skarn deposits

New World district, Mont.: Mine tailings from historic mining in the New World district have been washed downstream during large floods and especially during failure of the McLaren mine tailings impoundment along Soda Butte Creek in 1950 (Meyer, 1995). The site is along Soda Butte Creek, not at the McLaren mine itself, which is a few km to the north. The site has been investigated by EPA for remediation of acid mine drainage (SCS Engineers, 1984). Redeposited sand to clay-size sediment thins from a 35 cm-thick layer near the tailings failure to a layer a few cm thick 30 km downstream; lead and copper abundances in sediment decrease (from 1,200 to 300 ppm) downstream (Meyer, 1995). Preliminary studies of soil samples from meadows downstream from the tailings indicate patchy areas of low soil pH (3.5 to 4.0), low species diversity, and high abundances of toxic elements (Stoughton, 1995). Water data collected for the EPA site investigation are summarized above (see section entitled

"Drainage signatures).

Ok Tedi, Papua New Guinea: A number of recent studies address behavior of metals discharged in particulate form directly into the Fly River from mine tailings from the Ok Tedi porphyry copper and copper-gold skarn deposit (Salomons and Eagle, 1990; Apte and others, 1995). Mine tailings enter an upper tributary of this large tropical river because high rainfall and site instability preclude construction of adequate waste-retention structures. In water draining this area, calcium and bicarbonate ion concentrations are elevated because of abundant carbonate rock in the drainage area; bicarbonate ions buffer pH levels. Copper solubility is controlled by high concentrations of dissolved organic carbon and high alkalinity of the system; copper largely remains in particulate form (Salomons and Eagle, 1990). Copper-enriched sediment that is transported to an estuarine environment interacts with water having a different chemistry (greater concentrations of magnesium, calcium, and sodium) that leads to cation exchange reactions and release of copper in soluble forms.

Effects of metals associated with these deposits types on life

Plants: Copper is an important nutrient for plants; low soil copper contents (<10 ppm) may stress vegetation whereas high copper contents may be toxic.

Animals: Copper, iron, and zinc are essential elements for all animals. The effects of metals on animals depends on the bioavailability of metals ingested, and therefore, on the behavior of the metals in soil, plants, and water. Elevated metal concentrations in soil and plants, especially lead and arsenic can cause chronic toxicity. Metal deficiencies in ruminant animals are well-documented. Regional stream sediment geochemical surveys have been used in Great Britain to explore possible relations between geochemical environment and disease in animals due to inorganic element deficiencies or excesses (Bowie and others, 1985). The effects of metals are complex, because chemically similar elements, or elements that share metabolic pathways, may interact in the digestive tract. Absorption of copper as a nutrient, for example, can be inhibited by intake of high concentrations of zinc, cadmium, molybdenum, sulfur, iron, or silver and result in a copper deficiency syndrome.

Humans: Copper compounds in air, water, soil, sediment, and rocks are generally not harmful to humans because copper is strongly bound to soil or particles, or incorporated in insoluble minerals. Soluble forms of copper released into rivers and lakes are readily sorbed to particles. Copper is essential for human health and is not known to be a carcinogen (Agency for Toxic Substances and Disease Registry, 1989). Although cadmium is extremely toxic to animals and plants (as little as 1 to 10 ppm cadmium affects plant growth), much cadmium also apparently enters the human environment in cigarette smoke (Francis, 1984).

PERSPECTIVE

The following commentary is generally applicable to all three skarn-related geoenvironmental models. Extensive buffering capacity afforded by limestone suggests that skarn deposits should be less likely point sources of acid mine drainage than many other deposit types. The efficacy of limestone as a natural mitigant for acid mine drainage depends on its availability and on economic considerations. Some limestone is commonly present near most skarn deposits, but some roof pendants in granitoids, originally composed of limestone, are completely converted to skarn. In many skarn deposits, calcite and other minerals, such as epidote and chlorite, characteristic of propylitic alteration are disseminated or vein gangue minerals in ore zones. These minerals also increase the ability of the host rock to consume acid (Smith and others, 1994).

In their study of factors controlling acidity and metal concentrations in water draining mines developed in various types of mineral deposits in Colorado, Plumlee and others (1993) showed that important factors include acid-buffering capacity of ore deposit gangue minerals and host rocks, types and abundances of sulfide minerals and their exposure to weathering processes, and availability of dissolved oxygen. No skarn deposits were included in their study; however, their results, with regard to variations in aqueous base-metal concentrations as a function of pH for high-sulfide mineral, carbonate-hosted deposits and low-sulfide mineral carbonate-hosted deposits, represent the most appropriate available analog for predicting mine drainage signatures for skarn deposits. The length of time that sulfide-mineral-bearing deposits are exposed to oxidation may play a significant role in their eventual contribution to local, undisturbed environments as well as environments disturbed by mining. Some originally sulfide-mineral-bearing skarns have been thoroughly oxidized as a result of having been exposed during the last 35 million years.

Many mineralized skarn deposits are point sources for metals within much more widely altered mineralized systems, particularly porphyry systems. Some mineralized skarns may have potential for significant acid mine water development. However, none of the 61 mining-related sites on the Environmental Protection Agency (1995) National Priority List (Superfund) include skarn deposits. A number of skarn deposits, however, appear on lists of legal cases

that resulted from reported environmental damage (SCS Engineers, 1984). These include deposits where historic mine tailings contribute to water quality degradation and, in some cases, affected aquatic life. The extent of degradation from historic mining appears to be related to the magnitude and duration of operations as well as deposit type and climate. Any area that was extensively mined for long periods of time is likely to have experienced some environmental impact.

Skarn deposits that enter production today cannot be compared with skarn deposits worked a hundred, or even twenty, years ago. Many currently active mining or exploration projects involving skarn deposits operated at some time in the past at a smaller scale and are currently being re-evaluated for different metals (gold, silver) than were sought in past enterprises. Many abandoned or inactive skarn deposits are the focus of recent exploration because of economic changes or development of modern technology that allows previously uneconomic ore to be mined. For example, skarns that were mined in the past for base metals or tungsten may now constitute exploration targets for gold. Known or potential environmental hazards from historic mining can, in some cases, be mitigated by reopening the site to mining activity that involves reprocessing historic tailings using modern mining practices.

REFERENCES CITED

- Andrews, R.D., 1975, Tailings-Environmental consequences and a review of control strategies, *in* International conference on heavy metals in the environment, Symposium proceedings, v. 2, Toronto, 1975, p. 645-675.
- Apte, S.C., Benko, W.I., and Day, G.M., 1995: Partitioning and complexation of copper in the Fly River, Papua New Guinea: *Journal of Geochemical Exploration* 52, p. 67-79.
- Agency for Toxic Substances and Disease Registry, 1989, Public Health Statements.
- Bailey, R.G., Avers, P.E., King, Thomas, and McNab, W.H., eds., 1994, Ecoregions and subregions of the United States: U.S. Department of Agriculture Forest Service, 2 sheets, Scale 1:7,500,000.
- Beus, A.A., and Grigorian, S.V., 1977, Geochemical exploration methods for mineral deposits: Wilmette, Illinois, Applied Publishing Ltd., 287 p.
- Bowie, S.H.U., and Thornton, I., eds., 1985, Environmental geochemistry and health, Boston, D. Reidel Publishing Company, 140 p.
- Brooks, J.W., Meinert, L.D., Kuyper, B.A., and Lane, M.L., 1991, Petrology and geochemistry of the McCoy gold skarn, Lander County, Nevada, *in* Raines, G.L. and others, eds., Geology and ore deposits of the Great Basin, Symposium Proceedings, Geological Society of Nevada, Reno, p. 419-442.
- Broxton, D.E., 1979, Uranium hydrogeochemical and stream sediment reconnaissance data release for the Billings NTMS quadrangle, Montana, including concentrations of forty-three additional elements: U.S. Department of Energy Open-File Report GJBX-150(79), 200 p.
- Cox, D.P., 1986, Descriptive model of Zn-Pb skarn deposits, *in* Cox, D.P. and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 90.
- _____, 1992, Descriptive model of distal disseminated Ag-Au deposits, *in* Bliss, J.D., ed., Developments in mineral deposit modeling: U.S. Geological Survey Bulletin 2004, p. 20-22.
- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- Cox, D.P., and Theodore, T.G., 1986, Descriptive model of Cu skarn deposits, *in* Cox, D.P. and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 86.
- Doeblich, J.L., Wotruba, P.R., Theodore, T.G., McGibbon, D.H., and Felder, R.P., 1995, Field trip guidebook: Trip H- Geology and ore deposits of the Battle Mountain Mining District, Humboldt and Lander Counties, Nevada: Reno, Nevada, Geological Society of Nevada and U.S. Geological Survey, Geology and ore deposits of the American Cordillera, 92 p.
- Einaudi, M.T., and Burt, D.M., 1982, Introduction: terminology, classification, and composition of skarn deposits: *Economic Geology* v. 77, p. 745-754.
- Einaudi, M.T., Meinert, L.D., and Newberry, R.J., 1981, Skarn deposits: *Economic Geology* 75th Anniversary Volume, p. 317-391.
- Emmons, D.L. and Eng, T.L., 1995, Geologic map of the McCoy Mining District, Lander County, Nevada: Nevada Bureau of Mines and Geology Map 103, scale 1:12,000, 12 p.
- Environmental Protection Agency, 1995, National priorities list for uncontrolled hazardous waste sites (40 CFR Part 300): *Federal Register*, v. 60, no. 79, April 25, 1995, p. 20330-20353.
- Ettlinger, A.D., and Ray, G.E., 1989, Precious metal enriched skarns in British Columbia: An overview and geological study: British Columbia Ministry of Energy, Mines, and Petroleum Resources, Mineral Resources Division, Paper 1989-3, 128 p.

- Ficklin, W.H., Plumlee, G.S., Smith, K.S., and McHugh, J.B., 1992, Geochemical classification of mine drainages and natural drainages in mineralized areas, *in* Kharaka, Y.K., and Maest, A.S., eds., *Water-rock interaction: Seventh International Symposium on Water-Rock Interaction*, Park City, Utah, July 13-18, 1992, Proceedings, v. 1, Rotterdam, A.A. Balkema, p. 381-384.
- Francis, B.M., 1994, *Toxic substances in the environment*: New York, John Wiley and Sons, Inc., 360 p.
- Glass, N.R., Arnold, D.E., Galloway, J.N., Henry, G.R., Lee, J.J., McFee, N.W., Norton, S.A., Powers, C.F., Rambo, D.L., and Schofield, C.L., 1982, *Effects of acid precipitation: Environmental Science and Technology*, v. 15, p. 162A-169A.
- Hastings, J.S., and Harrold, J.L., 1988, Geology of the Beal gold deposits, German Gulch, Montana, *in* Schafer, R.W. and others, eds., *Bulk minable precious metal deposits of the western United States: Geological Society of Nevada, Symposium Proceedings*, April 6-8, 1987, Reno, NV, p. 207-220.
- Johnson, T.W., 1991, *Geology, hydrothermal alteration, and Cu-Ag-Au skarn and replacement mineralization in the northern part of the New World district, Park County, Montana*: Pullman, Washington State University, M.S. thesis, 326 p.
- Jones, G.M., and Menzie, W.D., 1986, Grade and tonnage model of Cu skarn deposits, *in* Cox, D.P. and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 86-89.
- Larocque, A.C.L., Laughlin, A.W., Hickmont, D., and Chapin, C.E., 1995, Metal-residence sites in weathered sulfide-rich tailings and sediments, Kelley mining camp, Magdalena District, New Mexico: *Geological Society of America Abstracts with Programs*, v. 20, no. 6, p. A-192.
- Loebenstein, J.R., 1994, *The materials flow of arsenic in the United States: U.S. Bureau of Mines Information Circular 9382*.
- Meinert, L.D., 1983, Variability of skarn deposits-guides to exploration, *in* Boardman, S.J., ed., *Revolution in the earth sciences: Dubuque, Iowa, Kendall-Hunt Publishing Co*, p. 301-316.
- _____, 1989, Gold skarn deposits-geology and exploration criteria, *in* Groves, D., Keays, R., and Ramsay, R., eds., *Proceedings of Gold '88: Economic Geology Monograph No. 6*, p. 537-552.
- Meyer, G.A., 1995, Tailings impoundment failure and floodplain sediment contamination along Soda Butte Creek, Yellowstone National Park, MT-WY: *Geological Society of America Abstracts with Programs*, v. 27, no. 4, p. 47.
- Mining Magazine*, 1994, *Minera Bismark*, p. 195-201.
- Mosier, D.L., 1986, Grade and tonnage model of Zn-Pb skarn deposits, *in* Cox, D.P. and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 90-93.
- Norman, D.K., and Raforth, R.L., 1995, Cyanide heap leaching-the process, environmental problems, and regulation in Washington: *Washington Geology*, v. 23, no. 1, p. 30-41.
- Plumlee, G.S., Smith, K.S., Ficklin, W.H., Briggs, P.H., and McHugh, J.B., 1993, Empirical studies of diverse mine drainages in Colorado: implications for prediction of mine-drainage chemistry: *Proceedings, 1993 Mined Land Reclamation Symposium*, Billings, Montana, v. 1, p. 176-186.
- Potter, W., Chang Ben, K-Y, and Adler, D., 1982, *The effects of air pollution and acid rain on fish, wildlife, and their habitats: Rivers and streams*, U.S. Department of Interior, Fish and Wildlife Service, FWS 14-16-0009-80-085.
- Ripley, E.A., Redman, R.E., and Crauder, A.A., 1995, *Environmental effects of mining: Delray Beach, Florida*, St. Lucie Press, 356 p.
- Salomons, W., 1995, Environmental impact of metals derived from mining activities: Processes, prediction, and prevention: *Journal of Geochemical Exploration*, v. 52, p. 4-23.
- Salomons, W., and Eagle, A.M., 1990, Hydrology, sedimentology and the fate and distribution of copper in mine related discharges in the Fly River system-Papua New Guinea: *Science of the Total Environment*, v. 97/98, p. 315-334.
- Sangmeshwar, S.R., and Barnes, H.L., 1983, Supergene processes in zinc-lead-silver sulfide ores in carbonates: *Economic Geology*, v. 78, p. 1379-1397.
- SCS Engineers, 1984, *Summary of damage cases from the disposal of mining waste: Unpublished report prepared for the U.S. Environmental Protection Agency*.
- Smith, K.S., Plumlee, G.S., and Ficklin, W.H., 1994, Predicting water contamination from metal mines and mining wastes: Notes, Workshop #2, *International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage: U.S. Geological Survey Open-File Report 94-264*, 112 p.

- Stoughton, Julie A., 1995, The spatial distribution of grasses, soils, and trace elements along the floodplains of Soda Butte Creek, Montana and Wyoming: Geological Society of America Abstracts with Programs, v. 27, no. 4, p. 57.
- Theodore, T.G., 1969, Surface distribution of selected elements around the Copper Canyon copper-gold-silver open-pit mine, Lander County, Nevada: U.S. Geological Survey Open-File Report, 21 sheets.
- Theodore, T.G., and Blake, D.W., 1975, Geology and geochemistry of the Copper Canyon porphyry copper deposit and surrounding area, Lander County, Nevada: U.S. Geological Survey Professional Paper 798-B, 86 p.
- _____ 1978, Geology and geochemistry of the West ore body and associated skarns, Copper Canyon porphyry copper deposits, Lander County, Nevada: U.S. Geological Survey Professional Paper 798-C, p. C1-C85.
- Theodore, T.G., Orris, G.J., Hammarstrom, J.M., and Bliss, J.D., 1991, Gold-bearing skarns: U.S. Geological Survey Bulletin 1930, 61 p.
- Torrey, C.E., Karjalainen, H., Joyce, P.J., Erceg, M., and Stevens, M., 1986, Geology and mineralization of the Red Dome (Mungana) gold skarn deposit, North Queensland, Australia, *in* Macdonald, A.J., ed., Proceedings of Gold '86, International Symposium on the Geology of Gold: Toronto, Geological Association of Canada, 1986, p. 3-22.
- Van Gosen, B.S., 1994, Genesis of the Homestake Breccia Au-Ag-Cu deposits, New World district, Cooke City, Montana: Golden, Colorado School of Mines, M.S. thesis, 158 p.
- White, D.E., Hem, J.D., and Waring, G.A., 1963, Data of Geochemistry-Chapter F. Chemical composition of subsurface waters: U.S. Geological Survey Professional Paper 440-F, 67 p.

FE SKARN DEPOSITS (MODEL 18d; Cox, 1986)

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James E. Elliott, J. Thomas Nash, David A. John, and K. Eric Livo

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

See general comments in the section entitled "Deposit Characterization" of the CU, AU, ZN-PB Skarn Deposits model (Hammarstrom and others, this volume).

Deposit geology

These deposits principally consist of magnetite in calc-silicate contact metasomatic rocks. Calcic magnetite skarns form in island-arc settings associated with relatively mafic (diorite) intrusions. Magnesian magnetite skarns form in orogenic belts along continental margins and are associated with felsic plutons in dolomitic host rocks as transitional zones, or in districts that contain copper-rich or tungsten skarn deposits. Most scapolite-(albite) iron skarn deposits are localized in basinal volcanic-sedimentary strata and are genetically related to late-stage phases of gabbroic and dioritic magmas.

Examples

Calcic iron skarn: Daquiri, Cuba; Empire, Vancouver Island, Canada; Shinyama, Japan.

Magnesian iron skarn: Fierro-Hanover, N. Mex.; Cornwall, Pa.; Eagle Mountain, Calif.

Scapolite-(albite) iron skarn: Kachar and Sarbay, U.S.S.R.; West Humboldt, Nev.

Worldwide, some of the largest iron skarn deposits are of the scapolite-(albite) variety (Zitzmann, 1977; Sokolov and Grigorev, 1977; Einaudi and others, 1981). In the classification scheme of Einaudi and others (1981), these deposits are categorized as the calcic-iron part of the twofold calcium-magnesium scheme. However, because of notable differences between scapolite-(albite) iron skarns and calcic and magnesian iron skarns we herein describe the scapolite-(albite) iron skarns separately, somewhat along the lines adopted by Zitzmann (1977). These differences include (1) the presence of widespread albite-(scapolite) assemblages in addition to garnet-pyroxene, (2) common development of endoskarn in contrast to calcic exoskarn, (3) extremely large tonnages, and (4) development in basinal volcanogenic strata as opposed to platform sequences consisting of thick miogeoclinal micrites.

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include base and precious metal skarns (Models 18b and c), tungsten skarns (Model 14a), porphyry copper deposits (Model 17). Magnetite-rich ore is mined as a by-product at a number of deposits. Examples include some of the Malaysian tin skarns, calcic zinc skarns in New Mexico, copper skarns at OK Tedi, Papua, New Guinea and Craigmont, British Columbia (Ray and Webster, 1990).

Potential environmental considerations

Magnetite is the principal ore mineral in iron skarns. Ore grades are typically 40 to 50 weight percent iron but these deposits have relatively low sulfide mineral contents and therefore relatively low acid-generating potential. In addition to the acid-buffering potential afforded by the common presence of carbonate-bearing strata, epidote (propylitic alteration of host rocks) also consumes acid. Magnetite is generally stable in the surface environment and persists as a heavy mineral in stream sediment during mechanical erosion. Furthermore, metals, including mercury, selenium, cadmium, and arsenic, that pose the most significant threats to the environment when they become bioavailable are not associated with most magnetite skarns. However, some scapolite-(albite) iron skarn in the West Humboldt, Nev., deposits contain as much as 15 ppm cadmium.

Exploration geophysics

Strong magnetic anomalies may be associated with these deposits; these anomalies become attenuated with increasing depth of burial or if magnetite has been converted to hematite. Airborne magnetic surveys have been used to identify large scapolite-(albite) iron skarn deposits in the U.S.S.R. In extremely weathered terranes, exposures of limonite, iron hydroxide, iron sulfate gossan, clay, or carbonate rock associated with these deposits may be identified by Landsat Thematic Mapper reflectance imagery. Very low frequency electromagnetic and induced polarization surveys may be used to identify magnetite and associated disseminated sulfide bodies. Resistivity surveys can be used to

model the distribution of alteration zones as indicated by ion content of water saturated rocks. Because of density contrasts between alteration mineral assemblages and deposit host rocks, microgravity surveys may be used to delineate the distribution of skarn deposits.

References

Einaudi and others (1981), Zitzmann (1977), and Cox (1986).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Mosier and Menzie (1986) present a deposit size range for iron skarns, undivided, expressed as percentiles of tonnages (in millions of metric tons) for a population of N deposits, whereas Einaudi and others (1981) present sizes for two iron skarn subtypes:

iron skarns, undivided (N=168): 0.33 (90th percentile) 7.2 (50th percentile) 160 (10th percentile)

Calcic iron skarn: 5 to 200 million t.

Magnesian iron skarn: 5 to 100 million t. Largest known deposit (234 million t) is Sherogesh, USSR.

Scapolite-(albite) iron skarn: 1 to 6,200 million t.

The 50th percentile value is the median deposit size for the population.

Scapolite-(albite)-magnetite iron skarns at Sarbay (Sarbai), in the Turgai Iron Province or mining district, U.S.S.R. (Sokolov and Grigorev, 1977), are among the largest iron skarns known: a geologic resource of approximately 2,894 million tonnes (t) of ore at a grade of about 43 weight percent iron was present prior to the onset of mining (D.L. Mosier, written commun., 1995). In addition, the nearby South Sarbay deposit contained 282 million t at 44 weight percent iron (Zitzmann, 1977). However, the scapolite-(albite)-magnetite iron skarn at Kachar, U.S.S.R., is even larger than those at Sarbay, and includes approximately 6,200 million t as a geologic resource to depths of 2.5 km at average grades of about 39 weight percent iron (Zitzmann, 1977).

The scapolite-(albite)-magnetite skarns at West Humboldt, Nev., are significantly smaller than those at Sarbay and Kachar: the largest deposits at West Humboldt are approximately 18 million t at about 47 weight percent iron (Reeves and Kral, 1955; Lowe and others, 1985).

Host rocks

Calcic iron skarn: Host rocks include limestone, sandstone, volcanic rocks, graywacke, dolomite at contacts of dioritic intrusions, within diorite, or at contacts of carbonate-bearing rocks with diabase flows.

Magnesian iron skarn: Host rocks are typically dolomite, or limestone, quartzite, and schist associated with dolomitic rocks.

Scapolite-(albite) iron skarn: Host rocks are andesite, tuff, limestone, argillite; endoskarn forms in gabbroic to dioritic intrusions.

Surrounding geologic terrane

Surrounding geologic terrane consists of batholiths, stocks, or plutons that intrude sedimentary sequences; scapolite-(albite)-magnetite iron skarns are present in volcanic-sedimentary basins.

Wall-rock alteration

Wall-rock alteration associated with calcic iron skarns involves extensive endoskarn development, which is characterized by albite, orthoclase, epidote, quartz, and scapolite, in plutons and volcanic rocks. Endoskarn associated with magnesian iron skarns is minor; propylitic alteration assemblages are characteristic.

Nature of ore

Ore consists of massive magnetite layers or lenses; orebodies are spatially associated with garnet zones or form in limestone beyond calc-silicate skarn zones. Calcic magnetite skarns and scapolite-(albite) iron skarns may be present within diorite stocks as replacements of gabbro and diorite or of limestone xenoliths (Einaudi and others, 1981). Stockwork veins may also be present in mafic volcanic rocks overlying altered gabbro. Orebodies may be lenticular, lensoid, tabular, contact-controlled deposits extending hundreds of meters to 4 km or more along strike and having thicknesses of tens to hundreds of meters, as well as irregular and pipelike, replacement of mafic intrusions and stockworks. Ore may be nearly monomineralic veins, pods, layers, or lenses of magnetite or may consist of magnetite-rich laminae or layers alternating with, or intergrown with gangue minerals. Ore mineral associations in

Table 1. Geochemical data for rock samples from the Hancock magnetite skarn, McCoy district, Lander County, Nev.

[Analyses by inductively coupled plasma and atomic absorption spectrophotometry; D. Fey, analyst. Oxides, in weight percent; trace elements, in ppm (Au, in ppb). N.d., not determined; FeTO3, total iron reported as Fe₂O₃]

Sample	1	2	3	4	5
TiO ₂	.20	.03	.12	.17	.17
Al ₂ O ₃	3.59	.36	1.13	3.02	1.08
FeTO ₃	93.0	102	41.6	47.2	5.01
MgO	5.64	1.82	2.65	6.14	14.9
CaO	.06	.04	28.0	15.5	12.0
Na ₂ O	.04	.03	.03	.19	1.05
K ₂ O	.77	<.06	.51	1.69	.20
P ₂ O ₅	<.01	<.01	<.01	<.01	.02
As	<10	<10	<10	<10	<10
Au	<50	<50	<50	<50	<50
Ba	270	21	81	320	49
Be	<1	<1	<1	<1	2.00
Cd	<2	<2	<2	<2	<2
Ce	<4	<4	38	19	30
Co	51	31	120	31	15
Cr	7	39	23	12	7
Cu	17	25	260	5	9
Ga	15	8	10	6	<4
La	<2	<2	36	18	20
Li	9	<2	5	15	16
Mn	930	736	646	375	504
Mo	<2	<2	<2	<2	<2
Nb	N.d.	N.d.	N.d.	N.d.	N.d.
Nd	<4	<4	10	5	13
Ni	51	<2	18	<2	120
Pb	28	6	9	7	33
Sc	4	<2	<2	<2	<2
Sn	<10	<10	<10	<10	<10
Sr	11	16	130	39	39
Th	8	9	<4	5	<4
V	300	280	370	88	100
Y	<1	<1	<1	<1	<1
Zn	120	20	16	8	13

1. Sample 85JH189- massive magnetite ore.
2. Sample 85JH190- massive magnetite ore.
3. Sample 85JH193- sulfide-mineral-rich magnetite ore.
4. Sample 85JH195- layered magnetite-tremolite-carbonate skarn.
5. Sample 85JH199- tremolite-magnetite skarn.

the Cornwall, Pa., skarn include magnetite-chalcopyrite-pyrite, magnetite-pyrite-actinolite, magnetite-chlorite, magnetite-hematite-calcite, and magnetite alone. Magnetite varies from anhedral and granular to euhedral and forms platy pseudomorphs after hematite (Lapham, 1968).

Deposit trace element geochemistry

Calcic iron skarn: iron, copper, cobalt, gold, and nickel.

Magnesian iron skarn: iron, copper, zinc.

Scapolite-(albite) iron skarn: iron, copper, zinc, lead, and arsenic, as well as trace amounts of cadmium.

See tables 1-3 for geochemical analyses of magnetite skarn ore and associated rocks. Table 1 presents previously unpublished data for magnesian magnetite skarn in dolomite adjacent to the Jurassic diorite stock at McCoy, Nev. (Stager, 1977). This skarn is older than the nearby copper-gold skarn deposit, which is associated with

Table 2. Geochemical data for rock samples from magnesian iron skarns, western Montana. [Analyses by inductively coupled plasma and atomic absorption spectrophotometry; B. Adrian, analyst. Oxides in weight percent; trace elements in ppm. FeTO₃, total iron reported as Fe₂O₃].

Sample	1	2	3
TiO ₂	<.01	.02	.23
Al ₂ O ₃	.62	.40	.60
FeTO ₃	44.2	38.8	33.9
MgO	3.76	9.69	11.4
CaO	1.16	.07	.63
Na ₂ O	.01	.01	.01
K ₂ O	<.06	<.06	<.06
P ₂ O ₅	<.01	.02	.21
As	<10	<10	<10
Au	<.05	<.05	<.05
Ba	5	2	2
Be	<1	<1	<1
Cd	<2	<2	<2
Ce	<4	<4	<4
Co	26	36	58
Cr	<1	2	7
Cu	4	2	3
Ga	10	10	6
La	<2	<2	<2
Li	2	3	3
Mn	988	1,640	1,821
Mo	<2	<2	<2
Nb	<4	5	11
Sn	<10	40	40
Sr	4	<2	<2
Th	4	4	7
Nd	<4	<4	<4
Ni	<2	11	6
Pb	<4	<4	<4
Sc	<2	<2	<2
V	13	35	17
W	2	5	2
Y	<2	<2	<2
Yb	<1	<1	<1
Zn	38	103	97

1. Pomeroy Mine, Southern Cross district, South Flint Creek Range, Mont., sample 89MT152 - massive magnetite.

2. Jumbo Mine, Beaverhead County, Mont., sample 89MT059 - magnetite ore.

3. Jumbo Mine, Beaverhead County, Mont., sample 89MT061-apatite-rich magnetite ore.

a 39-38 Ma granodiorite stock, currently being mined in the McCoy district. Minor amounts of pyrite and chalcopyrite are present in the magnetite skarn. Table 2 presents three previously unpublished analyses of magnetite

Table 3. Summary statistics for iron skarn analyses.

[Data from tables 1, 2, and Hammarstrom and Gray (1993, tables 2 and 3); N, number of analyses used to calculate means; qualified values were omitted from calculations. Oxides (in weight percent); trace elements in ppm (Au, in ppb)]

	N	Minimum	Maximum	Mean
TiO ₂	18	<.01	.78	.18
Al ₂ O ₃	19	0	17	5
FeTO ₃	19	3	102	44
MgO	19	0	15	4
CaO	19	0	28	8
Na ₂ O	18	<0.01	6	1
K ₂ O	14	<0.02	6	1
P ₂ O ₅	12	<0.01	.23	.10
As	2	<10	50	40
Au	9	<2	750	181
Ba	19	2	2,700	316
Be	2	<1	3	3
Cd	4	<2	6	5
Ce	7	<4	76	44
Co	19	6	120	44
Cr	14	<1	210	32
Cu	18	<2	2,100	432
Ga	16	6	28	15
La	7	<2	51	32
Li	15	<2	29	10
Mn	19	375	6,199	1,466
Mo	7	<2	22	10
Nb	3	<4	24	13
Nd	7	<4	46	21
Ni	15	<2	170	35
Pb	9	<4	40	17
Sc	10	<2	33	11
Sn	2	<10	40	40
Sr	16	<2	750	170
Th	7	<4	20	8
V	19	10	610	139
W	3	2	5	3
Y	5	<2	38	14
Yb	3	<1	4	3
Zn	19	8	310	94

skarn ore from two different deposits in western Montana--the Pomeroy Mine, a magnesian magnetite skarn along a contact between Upper Cambrian Pilgrim Dolomite and the Cretaceous Uphill Creek Granodiorite pluton of the Pioneer batholith. This pluton is associated with tungsten and copper-silver-gold skarns, including deposits of the Rock Creek district (see also, SN and (or) W skarn and replacement deposits model, Hammarstrom and others, this volume), that formed along contacts with limestone (Geach, 1972; Pearson and others, 1988). Ranges of iron skarn compositions from tables 1 and 2, for magnetite skarns in roof pendants of Mississippian Madison Limestone in the Sliderock Mountain area, Sweet Grass County, Mont., and data for iron-copper skarns in Cambrian Meagher Limestone along a granodiorite sill in the Independence mining district, Park County, Mont. (Hammarstrom and Gray, 1993), are summarized in table 3. These data represent nineteen samples from six different deposits, including magnesian as well as calcic skarn. No systematic differences in trace element content are apparent in the data set for dolomite- versus limestone-hosted skarn, so the data sets were combined. Table 4 summarizes previously unpublished data for the West Humboldt, Nev., scapolite-(albite) iron skarn deposits.

Table 4. Summary statistics for scapolite-(albite) iron skarn analyses for West Humboldt, Nev. [Data from G.B. Sidder, M.L. Zientek, and R.A. Zierenberg (written commun., 1995). Analyses by DC arc emission spectrography except for As, Bi, Cd, Sb, and Zn by inductively coupled plasma atomic emission spectrometry]

Sample type	Iron ore	Altered igneous wall rock
No. analyses ¹	17 (12)	29 (10)
Major elements, in weight percent ²		
Ca	.1-10 (1)	1-10 (3)
Fe	5->20 (>20)	3-15 (5)
Mg	.3-3 (1)	.7-3 (3)
Na	<.2-5 (<.2)	1.5-5 (3)
P	<.2	<.2
Ti	.07-.5 (.2)	.15-1 (1)
Trace elements, in ppm		
Ag	<.5-5 (<.5)	<.5-1.5 (<.5)
As	<5	<5
B	<10-30 (<10)	<10-200 (30)
Ba	<20-2,000 (50)	<20-300 (300)
Be	<1	<1-1.5 (<1)
Bi	<2-5 (<2)	<2
Cd	2.1-14 (12)	.6-7.3 (1.2)
Co	15-100 (30)	<10-200 (20)
Cr	<10-100 (10)	30-300 (150)
Cu	<5-30 (7)	<5-300 (10)
Ga	30-50 (30)	30-50 (30)
Mn	50-700 (150)	150-700 (500)
Mo	<5	<5
Nb	<20	<20
Ni	70-200 (150)	15-100 (50)
Pb	<10-30 (<10)	<10-20 (10)
Sb	<2-350 (<2)	<2-7 (<2)
Sc	<10-20 (<10)	10-30 (20)
Sn	<10	<10
Sr	<100-1,000 (<100)	<100-700 (500)
V	150-700 (300)	30-700 (150)
W	<20	<20
Y	15-70 (20)	15-50 (30)
Zn	8-37 (13)	<2-25 (8)
Zr	<10-100 (10)	30-150 (100)

¹Total number of analyses (number of analyses for As, Bi, Cd, Sb, and Zn).

²Range and (median) values.

Ore and gangue mineralogy and zonation

Calcic iron skarn:	Prograde- Garnet (grossular-andradite), pyroxene (ferrosalite). Retrograde- Amphibole, chlorite, epidote. Ore- Magnetite, chalcopyrite, cobaltite, pyrrhotite.
Magnesian iron skarn:	Prograde- Forsterite, calcite, spinel, diopside, magnetite, apatite, ludwigite-group minerals. Retrograde- Amphibole, humite, serpentine, phlogopite, talc, chlorite, chondrodite, magnesite, clinohumite. Ore- Magnetite, pyrite, chalcopyrite, sphalerite, pyrrhotite, arsenopyrite.
Scapolite-(albite) iron skarn:	Prograde- Garnet, pyroxene. Retrograde- Scapolite, albite, chlorite, calcite, zeolites, actinolite, epidote, apatite, quartz, prehnite, and sphene. Ore- Magnetite, hematite, pyrite, marcasite, chalcopyrite, sphalerite, pyrrhotite, and arsenopyrite.

Mineral characteristics

Magnetite typically forms massive layers or lenses. Sulfide mineral contents of magnetite skarns are generally low, but can be quite variable. Reported magnetite-pyrite ratios range from 100:1 to 3:1 for the Larap deposit in the Philippines; Larap is somewhat atypical of iron skarns because it contains economic concentrations of Cu, Mo, Au, Ag, Co, and Ni as well as Fe (Einaudi and others, 1981). At the Cornwall, Pa., magnetite mines, sulfide minerals were separated from magnetite; copper, gold, and silver were recovered from chalcopyrite and cobalt was recovered from pyrite.

Secondary mineralogy

Magnetite may alter to hematite, maghemite, goethite, limonite, or lepidocrocite during oxidation and weathering.

Topography, physiography

Iron skarns have little or no surface expression; however, in most cases, this depends on their resistance to weathering relative to adjacent rocks and on climatic setting.

Hydrology

These deposits have no known control on the local hydrologic regime.

Mining and milling methods

Most of these deposits have been exploited by open-pit methods; run-of-mine ore is fed directly to variable types of crushers and then sized through vibrating screens to mesh fractions appropriate for shipping. Comminuted ore is shipped as a concentrate and may be agglomerated by pelletizing or sintering prior to further processing (Ripley and others, 1995).

ENVIRONMENTAL SIGNATURES

Drainage signatures

No data are available for iron skarn deposits. However, chemical analyses of water from iron ore mines and milling operations in Canada (Ripley and others, 1995) are probably reasonable indicators of mine water discharge characteristics applicable to iron skarn deposits because Canadian iron ore has a low sulfide-mineral content and is dominated by magnetite, hematite, and siderite. This mine water and direct-discharge tailings effluent have pH of 6.4 to 9 and relatively low dissolved metal contents, including 0.01 to 0.4 mg/l copper, 0.05 to 1.3 mg/l iron, <1 mg/l lead, and 0.01 to 0.15 mg/l zinc. Much higher dissolved metal concentrations, including >40 mg/l copper and >6,000 mg/l iron, were reported for marine-discharge tailings effluent. Suspended solids may contribute to stream turbidity. Although iron is an essential nutrient for plants and animals, extreme iron concentrations downstream from historic, large-scale iron ore operations can be harmful to salmon and benthic organisms. However, residual materials from iron ore mining are generally considered to have minor toxicity.

Metal mobility from solid mine wastes

Typical final tailings associated with calcic iron skarn ore at Cornwall, Pa., which contains 40 to 42 percent iron, contain 7.7 weight percent iron, 0.61 weight percent sulfur, and 0.04 weight percent copper (Lapham, 1968). This iron concentration is similar to that, 7 to 9 weight percent, characteristic of typical iron ore tailings reported by Andrews (1975). Weathering of these tailings yields insoluble iron hydroxides.

Soil, sediment signatures prior to mining

Magnetite is commonly recovered as a heavy mineral in stream-sediment surveys. In industrialized areas in the Central Pyrenees Mountains, magnetite spheres were recovered in panned stream-sediment concentrates, and they have been interpreted as anthropogenic contaminants resulting from ash emission from an electric plant (Soler, 1991). In soil, magnetite is usually considered to be lithogenic rather than pedogenic although a number of studies suggest that magnetite may precipitate as a consequence of bacterial activity (Schwertmann, 1988).

Soil: The rate of iron oxide dissolution in soil is a function of mineralogy, particle size, and degree of crystallinity; in general, the reactivity of the iron oxide minerals in soil decreases as follows: ferrihydrate > lepidocrocite > magnetite > akageneite > hematite > goethite (Loeppert, 1988).

Potential environmental concerns associated with mineral processing

The relatively low sulfide mineral content of iron skarn deposits suggests that these deposits have relatively low acid-generating potential. Carbonate mineral-bearing strata that frequently host these deposits can buffer most of the acid generated by these deposits. Elevated abundances of metals that pose the most significant threats to the environment are not associated with most magnetite skarn deposits.

Smelter signatures

Iron ore is converted to iron by reduction to pig iron in blast furnaces or by direct reduction. The major impurities in iron ore result in relatively inert acidic (silica, alumina) or basic (lime, magnesia) slag during smelting.

Climate effects on environmental signatures

The effects of various climatic regimes on the geochemical signature specific to iron skarn deposits are not known. Because these deposits have relatively low sulfide mineral contents and because many are hosted by carbonate mineral-bearing strata that have abundant acid consumption potential, environmental signatures associated with iron skarn deposits are probably not much affected by climatic regime variation. The major effect of climate is probably the potential for physical disruption of tailings impoundments by flooding or wind.

Geochemical geophysics

Low spectral resolution reflectance imagery can be used to delineate the distribution of limonite, iron hydroxide, and iron sulfate gossan mineral assemblages in soil and water associated with iron skarn deposits. Similarly, magnetic surveys can be used to define the distribution of magnetite and pyrrhotite. Sulfide-mineral-rich bodies, whose oxidation may generate acid, metal-charged water, may be located using electromagnetic, induced polarization, and self potential surveys. Zones of leached rock altered to clay, mica, epidote, chlorite, and pyroxene may be delineated by resistivity surveys and using Landsat thematic mapper imagery and imaging spectrometer data. Remote sensing may be used to identify acid buffering carbonate rocks and stressed vegetation indicative of contaminated soil.

PERSPECTIVE

See section entitled "Perspective" in the CU, AU, ZN-PB skarn deposits model (Hammarstrom and others, this volume).

REFERENCES CITED

- Andrews, R.D., 1975, Tailings-Environmental consequences and a review of control strategies, *in* International conference on heavy metals in the environment, Symposium proceedings, v. II, Toronto, 1975, p. 645-675.
- Cox, D.P., 1986, Descriptive model of Fe skarn deposits, *in* Cox, D.P. and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 94.
- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- Einaudi, M.T., Meinert, L.D., and Newberry, R.J., 1981, Skarn deposits: Economic Geology 75th Anniversary Volume, p. 317-391.
- Geach, R.D., 1972, Mines and mineral deposits, Beaverhead County, Montana: Montana Bureau of Mines and Geology Bulletin 85, 194 p.
- Hammarstrom, J.M., and Gray, K.J., 1993, Geochemical data for selected rock samples from the Absaroka-Beartooth study area, Custer and Gallatin National Forests, Montana: U.S. Geological Survey Open-File Report 93-505, 31 p.
- Lapham, D.M., 1968, Triassic magnetite and diabase at Cornwall, Pennsylvania, *in* Ore deposits of the United States 1937-1967, The Graton-Sales volume, York, Pennsylvania, The Maple Press Co., v. I, p. 73-94.
- Loeppert, R.H., 1988, Chemistry of iron in calcareous systems, *in* Stuckli, J.W., Goodman, B.A., and Schwertmann, U., eds., Iron in soils and clay minerals: Boston, D. Reidel Publishing Company, Chapter 19, p. 689-713.
- Lowe, N.T., Raney, R.G., and Norberg, J.R., 1985, Principal deposits of strategic and critical minerals in Nevada: U.S. Bureau of Mines Information Circular 9035, 202 p.
- Mosier, D.L. and Menzie, W.D., 1986, Grade and tonnage model of Fe skarn deposits, *in* Cox, D.P. and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 94 -97.
- Pearson, R.C., Berger, B.R., Kaufmann, H.E., Hanna, W.F., and Zen, E-an, 1988, Mineral resources of the eastern Pioneer Mountains, Beaverhead County, Montana: U.S. Geological Survey Bulletin 1766, 34 p.

- Ray, G.E., and Webster, I.C.L., 1990, An overview of skarn deposits: Ore deposits, tectonics, and metallogeny in the Canadian Cordillera, Geological Society of Canada short course notes, p. 7-1-7-55.
- Reeves, R.G., and Kral, V.E., 1955, Geology and iron ore deposits of the Buena Vista Hills, Churchill and Pershing Counties, Nevada: Nevada Bureau of Mines Bulletin 53, Part A, 34 p.
- Ripley, E.A., Redman, R.E., and Crauder, A.A., 1995, Environmental effects of mining: Delray Beach, Florida, St. Lucie Press, 356 p.
- Schwertmann, U., 1988, Occurrence and formation of iron oxides in various pedoenvironments, *in* Stuckli, J.W., Goodman, B.A., and Schwertmann, U., eds., Iron in soils and clay minerals: Boston, D. Reidel Publishing Company, Chapter 11, p. 267-308.
- Sokolov, G.A., and Grigor'ev, V.M., 1977, Deposits of iron, *in* Smirnov, V.I., ed., Ore deposits of the U.S.S.R.: London, Pittman, v. 1, p. 7-113.
- Soler, A., 1991, Role of magnetite spheres in skarn exploration, *in* Skarns- their genesis and metallogeny: Athens, Theophrastus Publications S.A., p. 641-648.
- Stager, H.K., 1977, Geology and ore deposits of Lander County, Nevada: Nevada Bureau of Mines and Geology Bulletin 88, Part II, Mineral deposits, 106 p.
- Zitzmann, Arnold, 1977, The iron ore deposits of the western U.S.S.R., *in* Zitzmann, A., ed., The iron ore deposits of Europe and adjacent areas: Hannover, Bundesanstalt für Geowissenschaften und Rohstoffe, v. 1, p. 325-391.

POLYMETALLIC VEIN AND REPLACEMENT DEPOSITS (MODELS 19a and 22c; Morris, 1986; Cox, 1986)

by Geoffrey S. Plumlee, Maria Montour, Cliff D. Taylor, Alan R. Wallace, and Douglas P. Klein

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Deposits consist of massive lenses and (or) pipes, known as mantos or replacement orebodies, and veins of iron, lead, zinc, and copper sulfide minerals that are hosted by and replace limestone, dolomite, or other sedimentary rocks; most massive ore contains more than 50 percent sulfide minerals. Sediment-hosted ore commonly is intimately associated with igneous intrusions in the sedimentary rocks. Emplacement of these intrusions triggered ore formation and they host polymetallic veins and disseminations that contain iron, lead, zinc, and copper sulfide minerals. Some polymetallic replacement deposits are associated with skarn deposits in which host carbonate rocks are replaced by calc-silicate±iron oxide mineral assemblages. Most polymetallic vein and replacement deposits are zoned such that copper-gold ore is proximal to intrusions, whereas lead-zinc-silver ore is laterally and vertically distal to intrusions.

Examples

Leadville, Gilman, and Breckenridge districts, Bandora Mine, Colo.; Park City, Utah, district; Eureka, Nev., district; New World, Mont., district.

Spatially and (or) genetically related deposit types

Related deposit types (Cox and Singer, 1986) include Climax molybdenum (Model 16); porphyry molybdenum, low fluorine (Model 21b); porphyry copper (Model 17); porphyry copper-gold (Model 20c); porphyry copper-molybdenum (Model 21a); base metal skarns (Models 18a-d).

Potential environmental considerations

- (1) Many polymetallic vein and replacement deposits are hosted in carbonate-rich sedimentary rocks that consume acid and inhibit metal transport. However, mine water that drains deposits not hosted by carbonate-bearing rocks tends to be acidic to extremely acidic and contain elevated abundances of iron, aluminum, zinc, and copper and moderate abundances of lead, cadmium, and arsenic.
- (2) Water draining pyrite-rich, tailings and waste dumps can be acidic to highly acidic, and can contain high to extreme abundances of iron and aluminum, and very high abundances of zinc and copper.
- (3) Karst, where present, can impose significant control on the local hydrologic regime because of its ability to channelize ground water for long distances from mine sites.
- (4) Slag produced by smelting may contain elevated abundances of lead, zinc, and copper, and lesser amounts of other metals; the mobility of metals from slag varies as a function of how slag cooled.
- (5) Soil downwind from smelters can contain elevated abundances of Pb, Zn, Cu, As, Sb, Mo, Hg, and Au.

Mitigation and remediation strategies for potential environmental concerns presented above are described in the section below entitled "Guidelines for mitigation and remediation."

Exploration geophysics

Most massive sulfide replacement bodies have high density, low resistivity, are electrically chargeable when excited by induced polarization, have high magnetic susceptibility when magnetite or pyrrhotite are present, and may generate negative self-potential voltages (Ward, 1966; Buselli, 1980; Frischknecht and others, 1991; Fallon and Busuttill, 1992; Thomas and others, 1992). Consequently, these deposits often can be identified by detailed electrical, gravity, magnetic, and self-potential surveys. Specifics of particular geophysical responses are controlled by sulfide mineralogy, concentration, and continuity; hydrologic conditions; and by host and country rock characteristics and geometry. Airborne or ground-based electromagnetic, direct current resistivity, and induced polarization surveys can identify low-resistivity and chargeable sulfide masses, high-resistivity silicified-carbonitized zones, and pyritic alteration assemblages (Ward, 1966; Zonge and Hughes, 1991; Shalley and Harvey, 1992; Thomas and others, 1992). Anomalies initially identified by airborne electromagnetic and magnetic surveys can be further studied by ground-based geophysical surveys coupled with geologic and geochemical investigations. Targets for detailed exploration can also be selected using remote sensing data. Large (several hundred meters long) gossans can be identified on satellite-derived Thematic Mapper remote sensing images; smaller gossans may be detected using airborne imagery,

including aerial photography (Watson and Knepper, 1994), or AVIRIS imagery. Regional magnetic and gravity surveys may identify anomalies related to fault zones or intrusions that may control ore distribution or indicate prospective terrane (Fallon and Busuttil, 1992; Shalley and Harvey, 1992).

References

Geology: Lovering and others (1978), Beaty and others (1990), Titley (1993).

Environmental: Chaffee (1980; 1987), Plumlee and others (1993), Montour (1994), Smith and others (1994).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Deposits are small (10,000 tonnes) to very large (as much as 30-40 million tonnes).

Host rocks

These deposits are principally hosted by sedimentary rocks (dolomite, limestone, sandstone, and shale) that have been intruded by intermediate- to felsic-composition igneous stocks, dikes, and sills (figs. 1 and 2).

Surrounding geologic terrane

These deposits are in sedimentary rock sequences that host local igneous intrusions.

Wall-rock alteration

Carbonate-hosted replacement ore: Host carbonate rocks are commonly recrystallized, dolomitized, bleached, and (or) sanded (the process whereby carbonate cement is removed from sedimentary rocks). Alteration of carbonate rocks to silica-rich jasperoid is common locally in some districts. In some districts, carbonate minerals have been replaced by calc-silicate skarn minerals (epidote, amphibole, garnet, pyroxene, and iron oxide minerals) near their contacts with igneous intrusions (fig. 1).

Igneous-hosted ore: In the central, hottest parts of mineralized systems, igneous host rocks are altered to quartz-sericite-pyrite and quartz-clay (argillic) assemblages that grade into distal propylitic (epidote, chlorite, pyrite, carbonate) alteration assemblages.

Nature of ore

Ore is present in massive lenses (mantos), pipes (chimneys), and veins of iron, lead, zinc, and copper sulfide minerals that are hosted by and replace limestone, dolomite, or other sedimentary rocks; most massive ore contains >50 percent sulfide minerals. A given district or mine may contain a single, massive orebody or a series of orebodies aligned along structural features such as fractures, joints, fold limbs, stratigraphic features such as karst openings, or lithologic discontinuities (such as shale pinchouts) that control fluid movement (fig. 1). Manto and chimney ore is compact and can be relatively impermeable. Some ore replaces carbonate clasts in karst breccias, and may fill interstices between clasts.

Deposit trace element geochemistry

Polymetallic vein and replacement deposits are characterized by elevated abundances of Pb-Zn±Cu±Au±Ag±Mo±As±Bi±Sb. In some districts, ore proximal to igneous intrusions is copper and gold rich, and grades laterally (and sometimes vertically) into lead-zinc-silver-rich ore. A distal, manganese-enriched zone is present in some districts.

Ore and gangue mineralogy and zonation

Minerals listed in approximate decreasing order of abundance. Potentially acid-generating minerals are underlined; those that are acid-generating when oxidized by aqueous ferric iron are denoted by *.

Carbonate replacement ore: Pyrite, sphalerite*, galena*, siderite, quartz, marcasite, rhodochrosite, dolomite, chalcopyrite, pyrrhotite, tetrahedrite, digenite*, argentite, electrum, ± enargite, ± bornite, ± arsenopyrite, ±Bi-Te-Hg-Au-Ag minerals (hessite, petzite, pyrrargyrite, etc.), ± barite, ± fluorite. Most deposits are pyrite-rich; however, a few (rare?) deposits are pyrite-poor and are dominated by sphalerite and galena.

Igneous-hosted vein ore: Quartz, pyrite, chalcopyrite, sphalerite*, galena*, sericite, acanthite, gold/electrum, ± molybdenite, ± wolframite, ± scheelite.

Skarn ore: Magnetite, epidote, amphibole, pyroxene, ± serpentinite.

Zoning: In many deposits, ore grades from copper sulfide mineral-rich (chalcopyrite, enargite, bornite) within and near igneous intrusions, to sphalerite- and galena-rich away from intrusions, to sphalerite- and manganese carbonate-

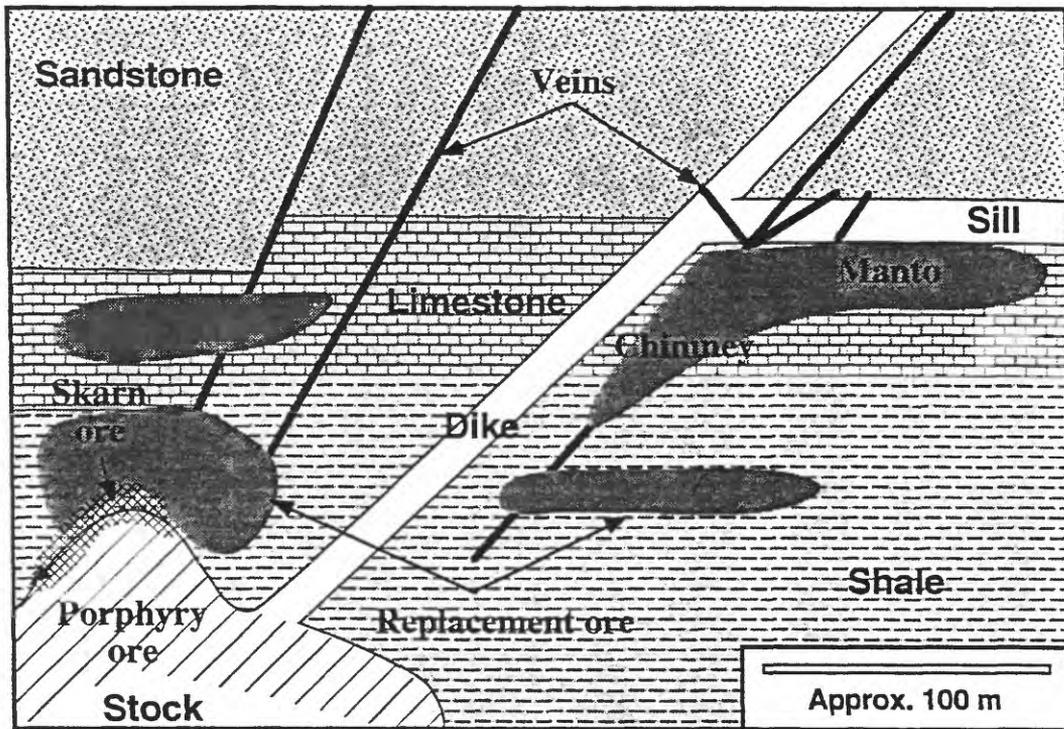


Figure 1. Schematic vertical section through a polymetallic replacement deposit showing distribution of ore types and host rocks.

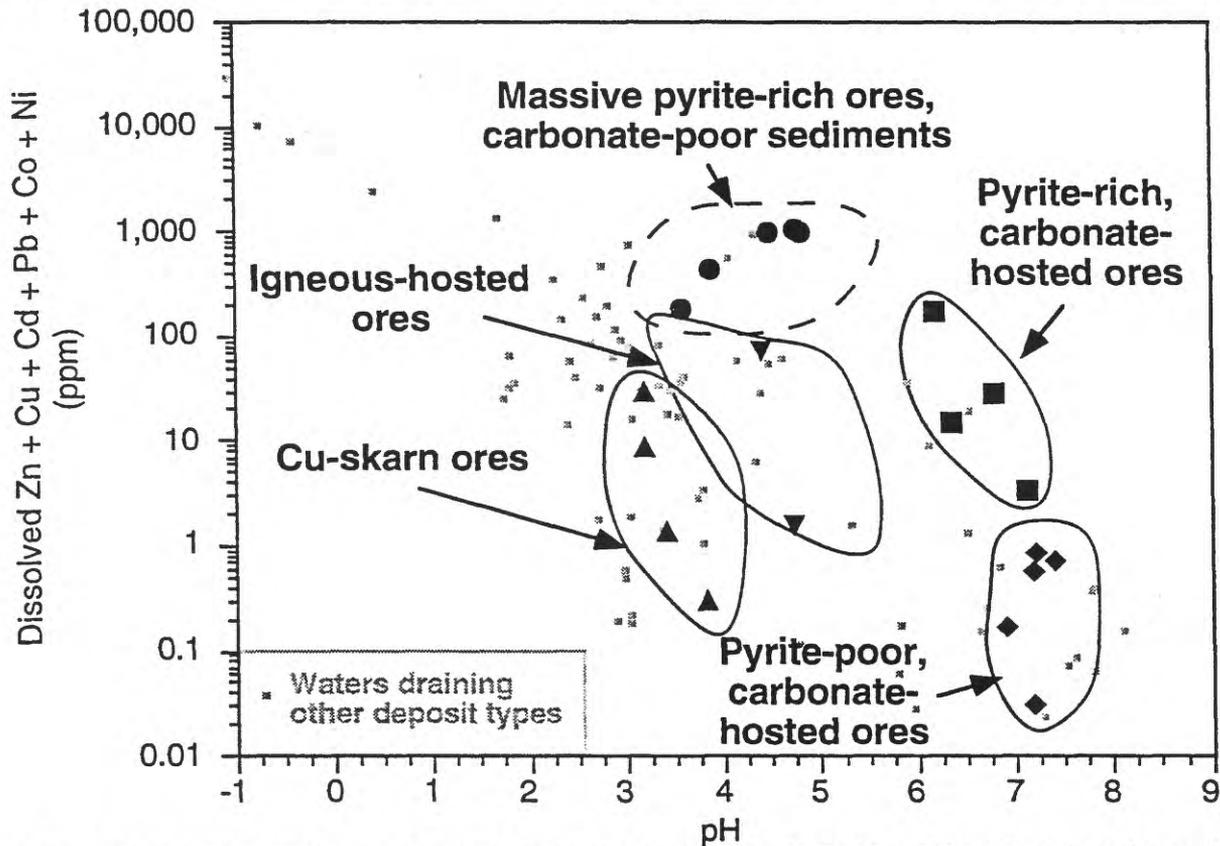


Figure 2. Ficklin plot showing pH versus the sum of dissolved base metals Zn, Cu, Cd, Co, Ni, and Pb in mine and natural water draining polymetallic replacement ore types.

bearing distal ore. Most skarn ore is near the intrusion-sedimentary rock contact.

Mineral characteristics

Textures: Mineral grains are typically medium to coarse grained (0.5 to >1 cm), and range in texture from euhedral to massive interlocking grains.

Trace element contents: In many deposits, sphalerite typically has very high iron contents (5-20 mol percent) and cadmium (several tenths to 1 mol percent) and minor amounts of other trace elements such as silver. Galena can contain silver and bismuth (generally <1 mol percent).

General rates of weathering: Euhedral to massive, interlocking sulfides weather at very slow rates. Samples exposed on mine dumps for >100 years are fresh and unweathered. Marcasite may weather at faster rates than pyrite, sphalerite, and galena. Fine-grained sulfide minerals weather more rapidly than those that are coarse-grained.

Secondary mineralogy

Readily soluble minerals underlined.

Minerals formed by weathering prior to mining: Carbonate ore— These minerals, including anglesite, cerussite, smithsonite, hemimorphite, hydrozincite, hemimorphite, manganese oxide minerals (psilomelane, pyrolusite, braunite), iron oxide minerals (limonite), cerargyrite, and jarosite, tend to be relatively insoluble and indicative of deposition from relatively high-pH water. Igneous ore—native gold, cerargyrite, and iron oxide minerals.

Minerals formed by recent weathering after the onset of mining: These minerals are primarily soluble sulfate minerals indicative of deposition from locally highly acidic water. Zinc sulfate minerals include goslarite, which grades to magnesium-rich epsomite. Iron sulfate minerals include copiapite, coquimbite, melanterite, szomolnokite, fibroferrite and roemerite. Chalcanthite is the dominant copper sulfate mineral although others may also be present.

Topography, physiography

Silica-rich orebodies in sedimentary and igneous rocks may form topographic highs.

Hydrology

Natural ground water flow in the vicinity of these deposits is dominantly along fractures and faults or through karst systems in carbonate rocks; mine workings enhance ground-water permeability. Karst, where present, can impose significant control on the local hydrologic regime because of its ability to channelize ground water for long distances from mine sites. Some flow may also occur in sedimentary rock aquifers, including sandstone and fractured carbonate rocks. Pre-mining discharge points may in some cases be determined by mapping surficial iron-hydroxide (ferricrete) deposits.

Mining and milling methods

Historic: Processing typically involved milling to produce zinc-, lead-, and (or) copper-rich concentrates that were subsequently smelted.

Modern: Processing typically involves milling; resulting concentrates are smelted. Stopes are backfilled by coarse tailings and fine tailings are stored in surface impoundments. Some copper-rich ore is currently being processed by sulfuric acid leaching and subsequent solvent extraction electrowinning.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Mine-drainage data (figs. 2 and 3): Data for Leadville, Kokomo, Breckenridge, and Bandora, Colo., from Plumlee and others (1993) and Smith and others (1994); data for New World, Mont., from Montana Department of State Lands (1994); data for Eagle, Colo., mine from Engineering Science, Inc. (1985).

(1) Mine water draining orebodies in carbonate-rich sedimentary rocks tends to be slightly acidic to near-neutral, pH 5.5 to 7.5; water draining pyrite-rich orebodies tends to contain tens to low hundreds of mg/l dissolved zinc. Water that drains copper-rich proximal ore can have several mg/l dissolved copper. Water with low dissolved oxygen content, such as that draining collapsed adits, can contain several tens of mg/l dissolved iron; as this water becomes oxygenated, oxidation and precipitation of iron can lead to significant pH decreases away from the drainage source. (2) Water draining igneous-hosted ore, ore in carbonate-poor sedimentary rock, and massive ore (in which water has limited interaction with host carbonate rocks) tends to be acidic (pH 3.5 to 5), contain several tens of mg/l iron and aluminum, tens to low hundreds of mg/l zinc, several to several tens of mg/l copper, and several hundred $\mu\text{g/l}$ lead,

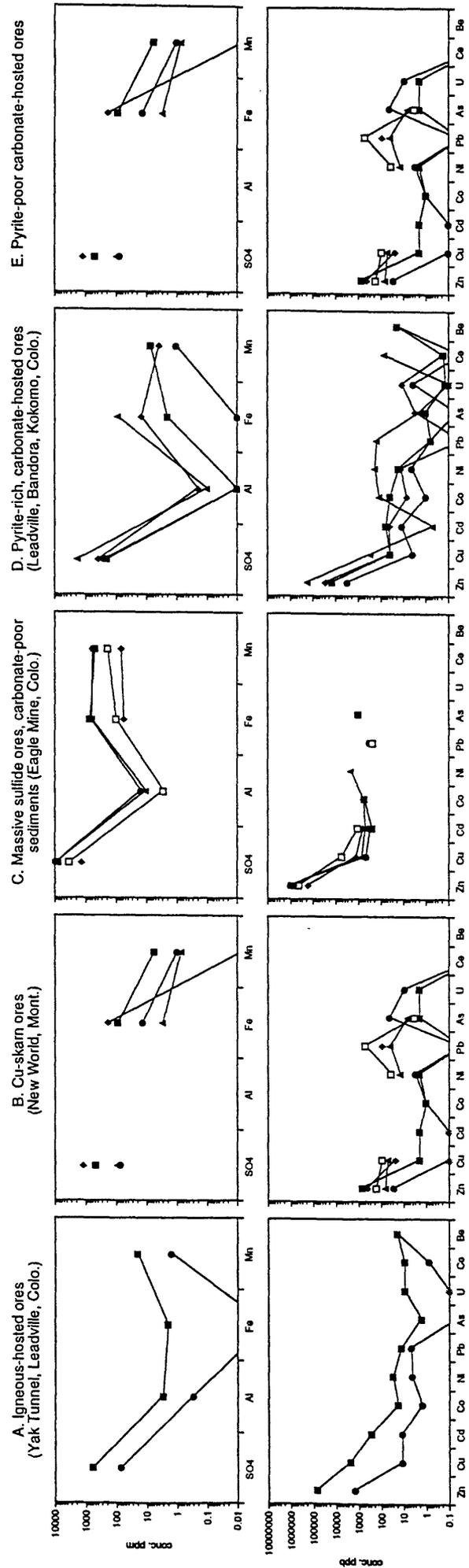


Figure 3. Dissolved concentrations of sulfate and major metals and various trace elements in mine water draining polymetallic replacement ore types. Data from Plumlee and others (1993), Smith and others (1994), Engineering Science, Inc. (1985), and Montana Department of State Lands (1994).

cadmium, and arsenic.

(3) Water draining pyrite-rich, carbonate-poor tailings and waste dumps tends to be acidic to highly acidic (pH 2 to 5), contains hundreds to several thousands of mg/l iron and aluminum, and tens to several hundreds of mg/l zinc and copper.

Natural-drainage data: Not available. However, anecdotal accounts indicate that cerussite, a lead carbonate mineral, was abundant in stream sediments downstream from Leadville, Colo.; the presence of cerussite indicates that associated stream water was not acidic. Cerussite was probably transported physically as eroded fragments of mineralized rock; however, the possibility that some lead was transported as an aqueous phase, and subsequently precipitated in stream sediments, cannot be ruled out entirely. Mine-water data suggest that pre-mining pH values at Leadville were near neutral (pH 6 to 7.5); this water may have contained as much as several mg/l zinc and several tens of $\mu\text{g/l}$ lead.

Potentially economically recoverable elements: Zinc extraction may become economically viable if aqueous extraction technologies continue to evolve.

Metal mobility from solid mine wastes

Metal mobility is greatest from mine dumps having the highest pyrite and lowest carbonate mineral contents. Metals and acid are readily liberated from pyrite-rich mine wastes and intermittently wet/dry mine workings due to the rapid dissolution of soluble secondary salts. In above-water-table settings, soluble salts form coatings on mine wastes, fracture fillings, and coatings on mine workings. The rate of salt dissolution (and resulting acid and metal generation) is much more rapid than acid consumption by carbonate minerals in the dumps or rocks surrounding the mine workings. Dumps with high carbonate mineral contents and low pyrite contents produce limited amounts of secondary salts; associated runoff has near neutral pH and low dissolved metal contents. In contrast, pyrite-rich, carbonate-poor dumps and mill tailings contain abundant secondary salts and down-gradient vegetation is adversely effected by acid, metal-rich drainage.

Storm water samples: No data available. However, extensive vegetation kill zones downhill from pyrite-rich mine dumps indicate that highly acidic, metalliferous water can be generated in spite of the presence of carbonate-mineral-rich rocks on the mine dumps.

Results of water-rock leaching experiments: Dilute sulfuric acid leaches of mine waste from Leadville, Colo., (Montour, 1994) using U.S. Environmental Protection Agency Method 1312 (20:1 water-rock ratio) yielded water with pH values mostly between 2 and 3; however, the pH of two samples was about 4 and several had pH values near 8. These leach samples also contained elevated metal abundances, including as much as 350 mg/l iron, 16 mg/l manganese, as much as 22 mg/l aluminum, as much as 250 mg/l zinc, and as much as 2,500 mg/l sulfate.

Dilute sulfuric acid leaches of smelter slag and soil affected by smelter particulates generally yielded much lower (<1 mg/l) abundances of lead and other metals than mine wastes (Montour, 1994). Mobility of metals from slag is a function of the way in which slag was cooled; metals in slag poured onto the ground generally are less readily liberated into the environment than those from slag cooled by frothing into the air (John Drexler, oral comm. to M. Montour, 1993).

Bioavailability studies: Results of bioavailability studies at Aspen, Colo., document the importance of particle mineralogy and size on lead bioavailability (Andy Davis, PTI Environmental, oral presentation, 1993). Lead in galena from mine wastes may be significantly less bioavailable than lead in smelter particulates and auto emissions.

Soil, sediment signatures prior to mining

Soil: Arid climate- Geochemical data for soil in the vicinity of polymetallic replacement deposits in the Eureka, Nev., district are presented by Chaffee (1980; 1987). Fine-grained fractions (<0.063 mm) of soil samples uncontaminated by smelter emissions contain elevated metal abundances, including as much as 10,000 ppm lead, as much as 30,000 ppm zinc, as much as 50 ppm cadmium, as much as 500 ppm copper, as much as 30 ppm molybdenum, as much as 100 ppm bismuth, as much as 400 ppm antimony, as much as 200 ppm tin, and as much as 30 ppm silver. Temperate climate- Limited soil geochemistry data (Montour, 1994) were obtained for samples collected beneath an historic residence in Leadville, Colo.; data for samples from these particular sample sites are presumed to reflect baseline metal abundances in soil unaffected by smelter contamination. This soil contains <100 ppm lead and <5 ppm cadmium. This soil is derived from unmineralized glacial outwash; its geochemistry should not be extrapolated to soil developed on mineralized bedrock, which probably contained substantially higher metal abundances.

Stream sediments: Very high lead concentrations identified in downstream sediment prior to mining at Leadville, Colo., probably reflect the abundance of cerussite.

Potential environmental concerns associated with mineral processing

Historic processing typically involved milling to produce zinc-, lead-, and (or) copper-rich concentrates that were smelted. Pyrite-rich tailings produced as a milling by-product have high potential for generation of highly acidic, metal-bearing water, especially if the water is evaporatively concentrated. Storm-related flushing of soluble secondary salts may also lead to periodic degradation of downstream surface water quality.

Modern processing typically involves milling followed by concentrate smelting; stopes are backfilled with coarse tailings materials and fine tailings are stored in surface impoundments. If pyritic tailings are backfilled, potential detrimental environmental effects can be largely avoided. In modern operations, gold-rich ore is increasingly recovered using a cyanide-free flotation system. Copper-rich ore may be treated using flotation. Some copper-mining operations use sulfuric acid heap leaching, followed by solvent extraction-electrowinning, to extract copper. The primary drawback of the acid-leach method for copper recovery is generation of potentially large volumes of acidic, iron- and aluminum-rich waste water that must be treated.

Smelter signatures

Chaffee (1980) demonstrated that soil geochemistry data effectively discriminates samples contaminated by smelter emissions from uncontaminated samples.

Leadville (Montour, 1994): Slag contains 1,500 to 3,400 ppm lead and 5 to 15 ppm cadmium; mineralogical studies indicate that most of the lead is present in sulfide minerals that survived smelting. Residential soil downwind from smelters contains more than 2,700 ppm lead and 5 to 37 ppm cadmium.

Eureka, Nev. (Chaffee, 1980; 1987): Soil in the vicinity of two smelters contains >1,000 ppm lead, >500 ppm arsenic and zinc, >100 ppm antimony and copper, >200 ppm tin, and >15 ppm molybdenum.

Climate effects on environmental signatures

Currently available data for mine water pertain to moderately wet, seasonally temperate climates. Evaporation of acid water during dry periods increases metal abundances and decreases pH. No data are available concerning evaporation of near-neutral water draining carbonate-hosted ore; evaporation of iron-poor water probably causes pH to increase.

Potential environmental effects:

Potential downstream effects of mine-drainage water associated with polymetallic replacement deposits are probably significantly less than those associated with other deposit types because of the abundance of near-neutral mine water and carbonate sedimentary rocks surrounding these deposits. Water draining carbonate rock terranes is highly alkaline and can effectively buffer acid generated by deposits or resulting from the formation of hydrous ferric and aluminum oxide particulates. In these situations, zinc and manganese are the elements most likely to remain mobile either in solution or as colloids (Kimball and others, 1995) for appreciable distances downstream.

The greatest potential for deleterious downstream environmental effects of mine-drainage water is associated with deposits principally composed of igneous or skarn ore; copper, zinc, manganese, and cadmium, to a lesser extent, can remain mobile for considerable distances downstream. In addition, deposits that contain abundant massive-sulfide ore in carbonate-poor sedimentary rocks, or carbonate-hosted massive sulfide ore in which drainage water does not interact with carbonate-rich sediments pose significant potential for environmental degradation. These ore types generate acidic, metal-rich water (figs. 2 and 3). Deposits that drain into geologic terranes with low acid-buffering capacity, such as those with low amounts of carbonate-bearing rocks, may also pose significant environmental hazards.

The most deleterious historic environmental effects associated with this deposit type are related to mining operations that released significant large volumes of fine-grained pyritic tailings into rivers or streams; these tailings have become part of accumulated sedimentary deposits, especially in low-velocity reaches of drainages. Oxidation of these tailings results in long-term release of metals and acid from sediments into overlying stream water resulting in water quality degradation; these downstream effects can be extensive.

Geoenvironmental geophysics

Distributions of conductive acid water can be delineated using electromagnetic and direct current resistivity surveys, and in some cases, ground penetrating radar (King and Pesowski, 1993; King, 1995; Paterson, 1995). Local hydrologic conditions, including permeable fault zones, bedrock channels, shallow caves, sandy flow channels, and clay aquitards, may be investigated using ground electrical, radar, seismic, magnetic, and gravity surveys. The same

methods can help define structural relations in tailing heaps (Paterson, 1995). Induced polarization can be utilized to estimate pyrite concentrations in tailings heaps (Paterson, 1995). Remote sensing imagery (Watson and Knepper, 1994; King, 1995) can help identify tailings distributions; bedrock lithologies, including acid-buffering carbonate rocks; and important structures that may control fluid flow.

Guidelines for mitigation and remediation:

- (1) Acid water draining igneous and skarn ore, some massive sulfide lenses, and tailings can be remediated successfully using lime addition and sodium-bisulfide precipitation of metals; this process yields a potentially acid-generating sludge. Lime addition to iron-rich drainage water may generate a quantity of suspended particulates, onto which a major fraction of dissolved arsenic, lead, and copper can sorb, sufficient to reduce or eliminate the need for sodium bisulfide addition; this particulate sludge is non-acid-generating.
- (2) Dilution of low-oxygen, near-neutral mine-drainage water by fresh water from carbonate aquifers may provide a low-cost remedial option, if sufficient dissolved iron is present to sorb metals.
- (3) The utility of carbonate sedimentary host rocks should be considered in acid drainage mitigation. For example, acid water could be channeled through artificially or naturally fractured carbonate rocks, away from orebodies, to help reduce acidity.
- (4) Careful fracture and karst mapping is required to adequately characterize site hydrology.
- (5) Isolation of pyrite-rich waste dumps from weathering and formation of soluble secondary salts is crucial to prevent storm- and snowmelt-related pulses of acid and metals into surface water. High carbonate mineral content of dump material is not sufficient to prevent acid pulses because secondary salt dissolution generates acid and metals much faster than the carbonates can react with and consume acid.
- (6) Backfilling the acid-generating, pyritic part of mill tailings into workings below the post-mining water table should be considered as a mitigative measure in modern milling operations to help avoid accidental downstream releases.
- (7) Future advances in aqueous zinc extraction technologies may render mine water draining these deposits a potentially economic zinc resource that can be used to help defray mitigation and remediation costs.

REFERENCES CITED

- Beaty, D.W., Landis, G.P., and Thompson, T.B., eds., 1990, Carbonate-hosted sulfide deposits of the central Colorado Mineral Belt: Economic Geology Monograph 7, 424 p.
- Buselli, G., 1980, Interpretation of Siro TEM data from Elura: Exploration Geophysics, Bulletin of the Australian Society of Exploration Geophysicists, v. 11, p. 264-271.
- Chaffee, M.A., 1980, Interpretation of geochemical anomalies in soil samples from a smelter-contaminated area, Eureka mining district, Nevada [abs.]: Technical Program, American Institute of Mining, Metallurgical, and Petroleum Engineers Annual Meeting, February, 1980, Las Vegas, Nevada, p. 56-57.
- _____, 1987, Application of R-mode factor analysis to geochemical studies in the Eureka mining district and vicinity, Eureka and White Pine counties, Nevada, in Elliott, I.L., and Smee, B.M., eds., GEOEXPO/86, Exploration in the North American Cordillera: Association of Exploration Geochemists, Vancouver, Canada, p. 94-108.
- Cox, D.P., 1986, Descriptive model of polymetallic veins, in Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 125.
- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- Engineering Science, Inc., 1985, Eagle mine remedial investigation, Appendix A: prepared for Colorado Department of Law, p. A11-A21.
- Fallon, G.N., and Busuttill, S., 1992, An appraisal of the geophysical effects of the Mount Isa ore bodies: Exploration Geophysics, Bulletin of the Australian Society of Exploration Geophysicists, v. 23, nos. 1/2, p. 133-140.
- Frischknecht, F.C., Labson, V.F., Spies, B.R., and Anderson, W.L., 1991, Profiling methods using small sources, in Nabighian, M.N., ed., Electromagnetic methods in applied geophysics-applications, Volume 2, Part A: Tulsa, Society of Exploration Geophysicists, p. 105-270.
- Kimball, B.A., Callender, E., and Axtmann, E.A., 1995, Effects of colloids on metal transport in a river receiving acid mine drainage, upper Arkansas River, Colorado, USA: Applied Geochemistry, v. 10, p. 285-306.
- King, A., Pesowski, M., 1993, Environmental applications of surface and airborne geophysics in mining: Canadian Institute of Mining and Metallurgy Bulletin, v. 86, p. 58-67.

- King, T.V.V., 1995, Environmental considerations of active and abandoned mine lands: U.S. Geological Survey Bulletin 2220, 38 p.
- Lovering, T.S., Tweto, O., and Lovering, T.G., 1978, Ore deposits of the Gilman district, Eagle County, Colorado: U.S. Geological Survey Professional Paper 1017, 90 p.
- Montana Department of State Lands, 1994, Abandoned priority hardrock mine priority sites: 283 p.
- Montour, M., 1994, Aqueous solubility of solid forms of lead in mining and smelting wastes, Leadville, Colorado: Boulder, University of Colorado, M.Sc. thesis, 234 p.
- Morris, H.T., 1986, Descriptive model of polymetallic replacement deposits, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 99-100.
- Paterson, Norman, 1995, Application of geophysical methods to the detection and monitoring of acid mine drainage, *in* Bell, R.S., ed., Proceedings of the symposium of the application of geophysics to engineering and environmental problems: Orlando, Florida, April 23-26, Environmental and Engineering Geophysical Society, p. 181-189.
- Plumlee, G.S., Smith, K.S., Ficklin, W.H., Briggs, P.H., and McHugh, J.B., 1993, Empirical studies of diverse mine drainages in Colorado--implications for the prediction of mine-drainage chemistry: Proceedings, 1993 Mined Land Reclamation Symposium, Billings, Montana, v. 1, p. 176-186.
- Shalley, M.J., Harvey, T.V., 1992, Geophysical response of the HYC deposit: Exploration Geophysics, Bulletin of the Australian Society of Exploration Geophysicists, v. 23, nos. 1/2, p. 209-304.
- Smith, K.S., Plumlee, G.S., and Ficklin, W.H., 1994, Predicting water contamination from metal mines and mining waste: Notes, Workshop #2, International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage: U.S. Geological Survey Open-file Report 94-264, 112 p.
- Thomas, G., Stolz, E.M., and Mutton, A.J., 1992, Geophysics of the Century zinc-lead-silver deposit, northwest Queensland: Exploration Geophysics, Bulletin of the Australian Society of Exploration Geophysicists, v. 23, nos. 1/2, p. 361-366.
- Titley, S.R., 1993, Characteristics of high-temperature, carbonate-hosted massive sulfide ores in the United States, Mexico, and Peru *in* Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., and Duke, J.M., eds., Mineral Deposit Modeling: Geological Association of Canada Special Paper 40, p. 585-614.
- Ward, S.H., 1966, Introduction-the search for massive sulfides, chapter III; Mining Geophysics volume I, Case Histories: Tulsa, Society of Exploration Geophysicists, p. 117-129.
- Watson, Ken, and Knepper, D.H., eds., 1994, Airborne remote sensing for geology and the environment-past and future: U.S. Geological Survey Bulletin, 1926, 43 p.
- Zonge, K.L., and Hughes, L.J., 1991, Controlled source audio-frequency magnetotellurics, *in* Nabighian, M.N., ed., Electromagnetic methods in applied geophysics-applications, Volume 2, Part B: Tulsa, Society of Exploration Geophysicists, p. 713-809.

AU-AG-TE VEIN DEPOSITS (MODEL 22b; Cox and Bagby, 1986)

by Karen D. Kelley, Theodore J. Armbrustmacher, and Douglas P. Klein

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Deposits consist of native gold and (or) gold-silver telluride minerals in high-grade quartz veins and (or) low-grade, near surface disseminated native gold and pyrite (with or without telluride minerals) in permeable host rocks. Porphyritic alkaline igneous rocks, many of which display explosive-magmatic features (diatremes, breccia pipes, or stockworks), are spatially and perhaps genetically associated with the deposits. Veins are localized along fracture zones; some veins are concentrated at intersections of crosscutting structural features. Disseminated deposits are commonly adjacent to major structures. Although wall-rock alteration associated with veins is restricted (fig. 1), alteration associated with disseminated deposits may be widespread within or near igneous centers.

Examples

Vein-type deposits: Cripple Creek, La Plata, Boulder County, and Rosita, Colo.; Horn Silver, Silver Queen, Sulphurets Camp, British Columbia, Canada; Judith Mountains (Warm Springs, Spotted Horse), Little Rocky Mountains (Zortman-Landusky), Golden Sunlight, Mont.; northern Black Hills (Annie Creek, Foley Ridge, and Richmond Hill), S. Dak.; White Oaks and Ortiz, N. Mex.; Emperor, Fiji; Musariu, Sacaramb, Romania.

Disseminated deposits: Cripple Creek, Colo.; Zortman-Landusky, Golden Sunlight, Mont.; Ortiz, N. Mex.; northern Black Hills, S. Dak.; Ladolam, Lahir Island; Porgera, Papua New Guinea.

Spatially and (or) genetically related deposit types

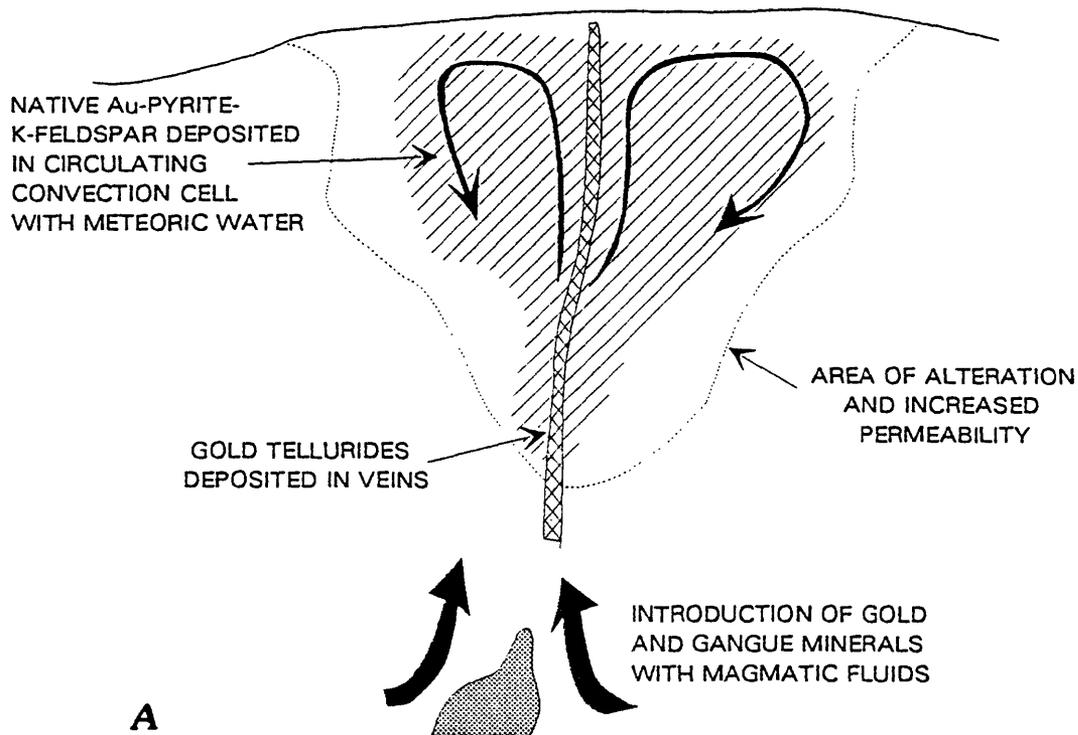
Associated deposit types (Cox and Singer, 1986) include alkaline porphyry copper (Model 17), porphyry gold-copper (Model 20c), polymetallic veins (Model 22c), polymetallic replacement (Model 19a), placer gold (Model 39a), distal disseminated silver-gold (Model 19c; Cox, 1992).

Potential environmental considerations

- (1) Vein deposits are mined dominantly by underground operations; vein clusters are mined in open-pits. Low-grade disseminated deposits are mined by open-pit operations. Most of these mining activities involve rocks with relatively low sulfur (in sulfide minerals) and high tellurium contents. Abundant carbonate minerals in alteration and gangue assemblages (and high CO₂ contents currently venting in some underground mines, for example Cripple Creek, Colo.) associated with these deposits create high acid-buffering capacity.
- (2) Water draining these deposits has low metal contents because pH is neutral to near-neutral. In areas underlain by rocks with low acid-buffering capacity, water draining open-pit mines may have elevated concentrations of iron, arsenic, copper, manganese, and zinc.
- (3) Soluble secondary minerals, including sulfate minerals, could cause short-term pulses of acidic, metal-bearing water from mine sites.

Exploration geophysics

Aeromagnetic and gravity studies (Kleinkopf and others, 1970) at Cripple Creek, Colo., show that geophysical anomalies are correlated with alteration intensity. Distribution of pyrite and clay in altered rock can be studied using induced polarization/resistivity. Brecciation, fracturing, and faulting associated with volcanic centers create pathways for pore water, oxidation of magnetite, and alteration of primary minerals to clay. Rock in these areas has low density, magnetization, and resistivity that can be identified by gravity, magnetic, and electromagnetic or direct current resistivity surveys. Potassic alteration and uranium and thorium in alkalic igneous rocks can be mapped by gamma-ray spectrometry. Aerial gamma-ray surveys (Pitkin and Long, 1977) identify anomalous potassium radiation associated with deposits at Cripple Creek, Colo. Alteration assemblages may be identified with multispectral remote sensing. Taranik (1990) successfully mapped the distribution of supergene iron oxide minerals using this technique. In addition, Livo (1994) characterized the distribution and nature of hydrothermal alteration using remote sensing techniques.



V E I N	
Secondary orthoclase	<p>Inner zone</p> <p>Biotite totally replaced by pyrite, magnetite, dolomite, secondary orthoclase, roscoelite-sericite, minor fluorite</p> <p>Plagioclase replaced by montmorillonite-sericite-roscoelite, minor carbonate</p> <p>Quartz unaltered to total recrystallization near vein</p> <p>Microcline rimmed and veined by adularia—up to 80 percent</p> <p style="text-align: center;">Outer limit 1 to 3X vein width</p> <hr style="border-top: 1px dashed black;"/> <p>Outer zone</p> <p>Biotite replaced by up to 95 percent sericite, secondary orthoclase, magnetite, pyrite, and carbonate</p> <p>Plagioclase replaced by up to 95 percent montmorillonite-sericite, minor carbonate</p> <p>Microcline and quartz—generally fresh, microcline weakly veined by adularia and quartz</p> <p style="text-align: center;">Outer limit 1 to 5X vein width</p> <hr style="border-top: 1px dashed black;"/> <p>Deuteric zone</p> <p>“Fresh rock,” biotite weakly replaced by chlorite and magnetite</p> <p>Plagioclase up to 50 percent covered by sericite-montmorillonite</p>
Dolomite	
Roscoelite	
Pyrite	
Magnetite	
Sericite	
Montmorillonite	

B

Figure 1. *A*, Conceptual model for a Au-Te system (based on Cripple Creek, Colo.; Pontius, 1992). Native gold and pyrite-rich disseminated deposits may be lateral or upper level equivalents to vein deposits. *B*, Vein-related wall-rock alteration (Thompson and others, 1985).

References

Kelly and Goddard (1969), Witkind (1973), Giles (1983), Mutschler and others (1985), Porter and Ripley (1985), Thompson and others (1985), Kay (1986), Saunders (1986), Ahmad and others (1987), Birmingham (1987), Afifi and others (1988), Saunders (1991), Pontius (1992), and Mutschler and Mooney (1995).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Typically 1-2 Mt (0.3-0.6 oz per ton) for vein deposits. Cripple Creek, Colo., one of the World's largest gold-telluride vein systems, has produced 41 Mt (average, 0.5 oz per ton); disseminated bulk minable deposits range from 32 Mt (0.037 oz per ton) at Cripple Creek to 66 mt (0.03 oz per ton) at Zortman-Landusky, Mont.

Host rocks

Most gold-silver-tellurium deposits are hosted in alkalic, silica-undersaturated rocks such as syenite, monzonite, diorite, phonolite, monchiquite, or vogesite; less common host rocks include silica-undersaturated low-titanium basalt (shoshonite). Except for calcic plagioclase, these rocks contain minerals with minimal acid buffering capacity.

Surrounding geologic terrane

Most gold-silver-tellurium deposits are associated with the late phases of orogenesis or failed rifting events; most deposits in the United States are along the eastern edge of the area affected by Laramide deformation and are in terranes composed of a variety of rock types, including metasedimentary, metavolcanic, carbonate, and volcanic rocks of diverse ages.

Wall-rock alteration

Alteration results from pre-ore igneous activity, vein-type mineralization, or disseminated gold and pyrite mineralization.

Igneous-related alteration: Argillization and dolomitization are characterized by weak to moderate clay alteration, sericitization, and minor recementing by dolomite; this type of alteration creates broad zones of increased permeability along major structures.

Vein-type deposits (fig. 1): Alteration is most extensively developed along vein junctions. Inner zone primarily consists of dolomite, adularia, sericite, roscoelite, and pyrite. Outer zone primarily consists of montmorillonite, sericite, adularia, magnetite, pyrite, and carbonate; this zone is typically 1 to 5 times (Cripple Creek, Colo.) vein width but locally extends as much as 20 times vein width (Boulder County).

Disseminated deposits: Potassium feldspar-pyrite alteration is characterized by pervasive flooding of fine-grained sanidine, orthoclase, and adularia along with moderate to strong sericitization and fine- to medium-grained pyrite. This alteration is most prominent in the broad vuggy permeable zones within 300 m of the surface. Strong potassium feldspar alteration creates a hardened porcelainous rock that resembles jasperoid.

Nature of ore

Vein deposits are usually high-grade but may be small and erratically distributed. Nearly all gold production from these deposits is from gold- and gold-silver telluride minerals. Base metals are infrequently present and are volumetrically minor. Most veins are structurally-controlled. Some structural zones display extensive vertical continuity; mineralized rock, with little evidence of mineralogic zoning or grade variation, can extend to depths of 1,000 m or more (Cripple Creek, Colo.). Lower-grade disseminated deposits containing native gold and auriferous pyrite may also be confined to structural intersections or major shear zones. Lower-grade deposits are best developed in permeable wall rocks, mostly igneous rocks or vent breccias, within 300 m of the surface.

Deposit trace element geochemistry

Trace element geochemical signatures depend on telluride mineralogy, but primary enrichments include Ag, As, Au, Ba, Bi, Cu, F, Fe, Hg, Mo, Mn, Ni, Pb, Sb, Te, V, and Zn. Both types of deposits appear to have had abundant CO₂ distributed throughout their vertical extent; deeper workings (Cripple Creek, Colo.) currently vent extensive amounts of CO₂ along major veins. These deposits are characterized by relatively low sulfur (in sulfide minerals) abundances, and usually by Au>Ag.

Ore and gangue mineralogy and zonation

Vein-type deposits: Ore minerals include gold-silver telluride minerals (calaverite, sylvanite), native gold and (or) native tellurium, and other telluride minerals (most commonly krennerite, petzite, hessite, coloradoite, melonite, altaite, tetradymite). Deposits also contain variable amounts of common base metal sulfide and sulfosalt minerals (pyrite, chalcopyrite, sphalerite, galena, and tetrahedrite); some deposits contain cinnabar. Gangue minerals include adularia, chlorite, fluorite, sericite, roscoelite, magnetite, hematite, barite, celestite, and carbonate minerals. The

generalized paragenesis includes early base-metal sulfide minerals, followed by telluride minerals (with or without native tellurium), hypogene native gold, and late-stage cinnabar. Quartz, fluorite, and pyrite are present throughout the sequence.

Disseminated deposits: Ore minerals are native gold, auriferous pyrite (as much as 2-3 percent), and occasionally telluride minerals (sylvanite, Zortman-Landusky, Mont.), although telluride minerals are often absent (Cripple Creek, Colo.). Gangue minerals include quartz, adularia, and fluorite.

Mineral characteristics

Carbonate minerals and quartz are dominant in banded, symmetrical veins. Ore minerals form groups of blades or small masses and locally, open-space fillings in vugs. In veins, complex intergrowths of several telluride minerals are common. In some case, minerals are so complexly intergrown that they cannot be easily identified. Breccia-filling textures are common in some deposits. Vein ore ranges from fine grained (0.01 to 1.5 mm) to coarse-grained, bladed crystals (0.5 to 2 cm). Low-grade disseminated deposits consist of microcrystalline native gold and pyrite disseminated in permeable host rocks.

Secondary mineralogy

Telluride minerals are easily destroyed by weathering. Some tellurium is redeposited as green oxide minerals (emmonsite). Native gold is deposited during supergene enrichment of some deposits. Late hydrothermal activity and oxidation of some deposits extends to depths of 30 to 180 m (Cripple Creek, Colo.; Zortman-Landusky, Mont.) and in others to depths of only 1.5 to 15 m (Boulder, Colo.). The depth of oxidation generally depends on the openness and permeability of vein structures. Late hydrothermal activity deposits a variety of sulfate minerals along with jarosite, anhydrite, opal, and chalcedony. A variety of iron (limonite) and manganese oxide minerals results from oxidation. Dolomite formed during early igneous-related activity and present within the oxidized zone may be leached during oxidation. Gott and others (1969) found that secondary geochemical dispersion results in anomalies of gold, silver, and tellurium, accompanied by enrichments of iron, lead, mercury, antimony, arsenic, and vanadium. A manganese-enriched outer halo is present commonly.

Topography, physiography

Alkaline intrusive and associated volcanic rocks commonly form topographic highs. However, if igneous-activity-related alteration, including argillization and dolomitization, is prevalent, broad high permeability zones, which are highly susceptible to increased erosion, may result. Alteration related to vein type mineralization is restricted in spatial extent and probably does not contribute to enhanced erosion.

Hydrology

Since these deposits are commonly structurally controlled, ground water flow is focused along high permeability structures. Numerous historic underground workings, typical of some districts, also control water recharge and discharge. Pre-mining ground water oxidizes rock to significant depths, for instance, 180 m at Cripple Creek. Contacts between igneous rocks and surrounding wall rock constitute significant ground water conduits. Since deposits are typically located at topographic highs associated with volcanic rocks, surface water flows radially away in all directions.

Mining and milling methods

Historic: Most historic operations involved underground workings along veins. Ore was processed by stamp mills, followed by mercury amalgamation or cyanide vat leaching. The second largest cyanide mill in the world was at one time located in Ruby Gulch (near the current Zortman-Landusky, Mont., mine).

Modern: Most modern operations are open-pit mines that exploit vein clusters or disseminated gold along major structures. Ore is processed primarily by cyanide heap leaching.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Natural drainage water: The only data concerning the geochemistry of natural water draining gold-silver-telluride veins are those for the Zortman-Landusky, Mont., deposit; data are part of environmental impact studies (Scott Haight, U.S. Bureau of Land Management office, Lewistown, Mont., oral commun., 1995; Zortman-Landusky area Environmental Impact Statement, 1995). Pre-mining (pre-1979) data from the Zortman-Landusky area indicate the

following:

(1) Surface water was slightly acidic to slightly alkaline (pH 6.9 to 8.4) and contained low dissolved constituent concentrations, including 8 to 134 mg/l sulfate, 0.002 to 0.01 mg/l arsenic, 0.011 to 0.17 mg/l iron, and 0.01 mg/l zinc.

(2) Groundwater was slightly acidic to slightly alkaline (pH 6.5 to 8.0) and contained low to moderate dissolved constituent concentrations, including 2 to 186 mg/l sulfate, 0.005 to 0.31 mg/l arsenic, 0.021 to 11 mg/l iron, and 0.005 to 0.88 mg/l zinc. Relatively higher concentrations of sulfate and metals in some water samples are due to the presence of shale, which has naturally high concentrations of sulfate and metals, in some drainage areas.

(3) Elevated concentrations of arsenic in some groundwater indicates that alluvial groundwater had been affected by historic, those conducted prior to open pit mining, mining activities.

Mine drainage water: Most mine water is neutral (pH 7 to 8), but slightly acidic water (pH 6.0 to 6.9) has been reported near the Zortman-Landusky, Mont., mine (U.S. Environmental Protection Agency, 1990). Most water draining from mines has low concentrations of total dissolved metals ($Zn+Cu+Cd+Co+Ni+Pb < 100 \mu\text{g/l}$) (Plumlee and others, 1993) but may have elevated concentrations of zinc (U.S. Environmental Protection Agency, 1990; Keffelew, 1995). Other metals, including iron, arsenic, copper, and manganese rarely are present in high concentrations but may be present at abundances that exceed Federal Secondary Drinking Water Standards (U.S. Environmental Protection Agency, 1990). At Cripple Creek, Colo., extensive areas of dolomitized rock, mostly at deep levels, and CO_2 , that is currently outgassing, buffer acidic solutions (Jeff Pontius, Pikes Peak Mining Company, oral and written commun., 1995). At Zortman-Landusky, surrounding carbonate rocks quickly buffer slightly acidic water (U.S. Environmental Protection Agency, 1990).

Potentially economically recoverable elements: Scandium abundances in Cripple Creek, Colo., mine drainage are relatively high and may represent an economically recoverable commodity (Geoff Plumlee, oral commun., 1995).

Metal mobility from solid mine wastes

Metal mobility away from gold-tellurium deposits may be limited if abundant carbonate rock, alteration assemblages, and (or) gangue minerals are associated with deposits. Water quality data from wells and springs in the Zortman-Landusky, Mont., area show that ground water in the area is hard to very hard, alkaline (pH 7 to 7.5), and of the calcium carbonate type. Surface water from a stream draining the waste and heap leach area is slightly acidic (pH 6 to 6.9) and contains as much as 297 $\mu\text{g/l}$ arsenic and 36 $\mu\text{g/l}$ cyanide (U.S. Environmental Protection Agency, 1990). Flow and water quality vary slightly with seasonal precipitation rates. During spring runoff, one stream contained elevated manganese abundances (U.S. Environmental Protection Agency, 1990).

Soil, sediment signatures prior to mining

Because most gold-tellurium deposits in the United States have been mined by underground and (or) placer mining methods since the late 1800s, including for instance, Boulder County and Cripple Creek, Colo., and Zortman-Landusky, Mont., pre-mining geochemical data for soil and sediment associated with these deposits are rare. However, data obtained in 1978, before initiation of open-pit mining and heap leaching operations, as part of the National Uranium Resource Evaluation program, are available for the Zortman-Landusky, Mont., area. Stream sediment samples collected from streams within 5 km of and draining mineralized areas contain <5 to 12 ppm silver, 0.04 to 0.4 ppm gold, <5ppm cadmium, 18 to 81 ppm copper, 1.4 to 4.2 weight percent iron, 200 to 2,020 ppm manganese, 7 to 197 ppm lead, and 70 to 1,131 ppm zinc (Shannon, 1980).

Potential environmental concerns associated with mineral processing

Mercury amalgamation of ore during historic operations may represent a source of mercury contamination not directly associated with these mineral deposits.

Historic cyanide milling operations at Zortman-Landusky, Mont., discharged waste water to watercourses (U.S. Environmental Protection Agency, 1990). Most modern heap leach operations rinse heap-leach residues, barren ore, remaining after the leaching cycle with fresh water to remove residual cyanide. Residues are left on heap leach pads. Heap leach and other cyanide processing solutions are most likely to include gold and silver cyanide complexes with lesser arsenic, antimony, nickel, vanadium, and iron present as weak cyanide complexes.

Smelter signatures

No data currently available.

Climate effects on environmental signatures

The effects of various climate regimes on the geoenvironmental signature specific to gold-silver-tellurium deposits are not known. However, in most cases the intensity of environmental impact associated with sulfide-mineral-bearing mineral deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell.

Geoenvironmental geophysics

Acid- or metal-bearing water resulting from pyrite oxidation has low resistivity and consequently can be identified with electromagnetic or direct current induced polarization/resistivity surveys and ground penetrating radar. Structural and stratigraphic features such as faults, bedrock topography, buried channels, and aquitards that affect water flow away from mine areas may be studied using electromagnetic or direct current resistivity, seismic refraction or reflection, magnetic, gravity, and ground penetrating radar surveys; water flow may be monitored using self potential methods. The distribution of supergene iron oxide and sulfate minerals, especially jarosite, as well as primary hematite may be identified using remote sensing techniques.

REFERENCES CITED

- Afifi, A.M., Kelly, W.C., and Essene, E.J., 1988, Phase relations among tellurides, sulfides, and oxides: II. Applications to telluride-bearing ore deposits: *Economic Geology*, v. 83, p. 395-404.
- Ahmad, M., Solomon, M., and Walshe, J.L., 1987, Mineralogical and geochemical studies of the Emperor gold telluride deposit, Fiji: *Economic Geology*, v. 82, p. 345-370.
- Birmingham, S.D., 1987, The Cripple Creek volcanic field, central Colorado: Austin, University of Texas, M.S. thesis, 295 p.
- Cox, D.P., 1992, Descriptive model of distal disseminated Ag-Au deposits, *in* Bliss, J.D., ed., *Developments in mineral deposit modeling: U.S. Geological Survey Bulletin 2004*, p. 20-22.
- Cox, D.P., and Bagby, W.C., 1986, Descriptive model of Au-Ag-Te veins, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 124.
- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: *U.S. Geological Survey Bulletin 1693*, 379 p.
- Environmental Impact Statement (draft version), 1995, Zortman and Landusky mines, v. 2.
- Giles, D.L., 1983, Gold mineralization in the laccolithic complexes of central Montana, *in* Proceedings Denver Region Exploration Geologists Society Symposium--The genesis of Rocky Mountain ore deposits: Changes with time and tectonics: Denver Region Exploration Geology Society, Denver, Colorado, p. 157-162.
- Gott, G.B., McCarthy, J.H., Van Sickle, G.H., and McHugh, J.B., 1969, Distribution of gold and other metals in the Cripple Creek district, Colorado: *U.S. Geological Survey Professional Paper 625-A*, p. A1-A17.
- Kay, B.D., 1986, Vein and breccia gold mineralization and associated igneous rocks at the Ortiz Mine, N. Mex., USA: Golden, Colorado School of Mines, M.Sc. thesis, 170 p.
- Keffelew, Berhan, 1995, Third party review of document entitled "Amendment No. 6 to Office of Mined Land Reclamation, Permit M-80-244, response to OMLR technical review, acid-base potential of Cresson mine overburden, September 1994, 22 p.
- Kelly, W.C., and Goddard, E.N., 1969, Telluride ores of Boulder County, Colorado: *Geological Society of America Memoir 109*, 237 p.
- Kleinkopf, M.D., Peterson, D.L., and Gott, G., 1970, Geophysical studies of the Cripple Creek mining district, Colorado: *Geophysics*, v. 35, no. 3, p. 490-500.
- Livo, K.E., 1994, Use of remote sensing to characterize hydrothermal alteration of the Cripple Creek area, Colorado: Golden, Colorado School of Mines, M.S. thesis, 135 p.
- Mutschler, F.E., Griffin, M.E., Stevens, D.S., and Shannon, S.S., Jr., 1985, Precious metal deposits related to alkaline rocks in the North America Cordillera--An interpretive review: *Transactions of the Geological Society of Africa*, v. 88, p. 355-377.
- Mutschler, F.E., and Mooney, T.C., 1995, Precious metal deposits related to alkaline igneous rocks--provisional classification, grade-tonnage data, and exploration frontiers: *Geological Association of Canada Special Paper--IAGOD 1990 Symposium on ore deposit models*, 22 p.

- Pitkin, J.A., and Long, C.L., 1977, Interpretation of data from an aerial gamma-ray survey in the Cripple Creek district, Teller County, Colorado: U.S. Geological Survey Open-File Report 77-534, 12 p.
- Plumlee, G.S., Smith, K.S., Ficklin, W.H., Briggs, P.H., and McHugh, J.B., 1993, Empirical studies of diverse mine drainages in Colorado: Implications for the prediction of mine-drainage chemistry: Proceedings, Mined Land Reclamation Symposium, Billings, Montana, p. 176-186.
- Pontius, J.A., 1992, Gold mineralization within the Cripple Creek diatreme/volcanic complex, Cripple Creek Mining district, Colorado, USA: International Minexpo 92, Las Vegas, Nevada, October 18-22, 12 p.
- Porter, E.W., and Ripley, E., 1985, Petrologic and stable isotope study of gold-bearing breccia pipe at the Golden Sunlight deposit, Montana: *Economic Geology*, v. 80, p. 1689-1706.
- Saunders, J.A., 1986, Petrology, mineralogy, and geochemistry of representative gold telluride ores from Colorado: Golden, Colorado School of Mines, Ph.D. thesis, 171 p.
- _____, 1991, Gold deposits of the Boulder County Gold District, in Shawe, D.R., and Ashley, R.P., eds., *Epithermal gold deposits--part II: U.S. Geological Survey Bulletin 1857-I*, p. I137-I148.
- Shannon, S.S., Jr., 1980, Uranium hydrogeochemical and stream sediment reconnaissance data release for the Lewistown NTMS quadrangle, Montana, including concentrations of forty-two additional elements: U.S. Department of Energy Report GJBX-206 (80), 128 p.
- Taranik, D.L., 1990, Remote detection and mapping of supergene iron oxides in the Cripple Creek district: Boulder, University of Colorado, M.S. thesis, 103 p.
- Thompson, T.B., Trippel, A.D., and Dwelley, P.C., 1985, Mineralized veins and breccias of the Cripple Creek district, Colorado: *Economic Geology*, v. 80, no. 6, p. 1669-1688.
- U.S. Environmental Protection Agency, 1990, Preliminary assessment of the Landusky mine (Zortman mine), Landusky, Montana: Environmental Protection Agency report MTD89515498.
- Witkind, I.J., 1973, Igneous rocks and related mineral deposits of the Barker quadrangle, Little Belt Mountains, Montana: U.S. Geological Survey Professional Paper 752, 58 p.

VOLCANIC-ASSOCIATED MASSIVE SULFIDE DEPOSITS
(MODELS 24a-b, 28a; Singer, 1986a,b; Cox, 1986)

by Cliff D. Taylor, Robert A. Zierenberg, Richard J. Goldfarb,
James E. Kilburn, Robert R. Seal II, and M. Dean Kleinkopf

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Volcanic-associated massive sulfide (VMS) deposits range from lens shaped to sheet-like bodies of sulfide-mineral-rich rock spatially associated with volcanic rocks ranging in composition from basalt to rhyolite (fig. 1). VMS deposits can be divided into three general categories. Cyprus-type deposits (Model 24a; Singer, 1986a) tend to be small, medium-grade deposits rich in copper and zinc. They are generally lens or mound shaped accumulations of massive pyrite developed in ophiolite-related, extrusive basalt sequences. They are typically underlain by copper-rich "stringer-zones" composed of anastomosing quartz-sulfide mineral veins in extensively chloritized basalt. Kuroko deposits (Model 28a; Singer, 1986b) are typically developed in intermediate to felsic volcanic rock and are generally interpreted to have formed in extensional environments associated with arc volcanism. They are commonly high grade and can be very large. Relative to Cyprus-type deposits, they generally have much higher contents of zinc, lead, silver, and antimony, which reflects the composition of their felsic volcanic host rocks. They also have mound-like morphology and the abundance of coarse clastic sulfide minerals within many of these deposits attests to a moderately high energy, seafloor depositional setting. Kuroko-type deposits also tend to be underlain by copper-rich stringer zones and commonly have well developed geochemical zonation with progressive zinc, lead, and silver enrichment both vertically and laterally away from vent centers. Besshi-type deposits (Model 24b; Cox, 1986) are present in mixed volcanic-sedimentary environments. Deposits of this type are commonly hosted by turbidites that have been intruded by basaltic sills. These deposits are typically copper-rich and contain small abundances of lead and other lithophile elements. In contrast to other volcanic-hosted deposits, many Besshi-type deposits form thin, laterally extensive sheets of pyrrhotite- and (or) pyrite-rich massive sulfide rock; however, the characteristics of Besshi-type deposits vary considerably. Slack (1993) presents an expanded definition of Besshi-type deposits that includes deposits such as those in the Ducktown, Tenn., district and the large Windy Craggy deposit in British Columbia.

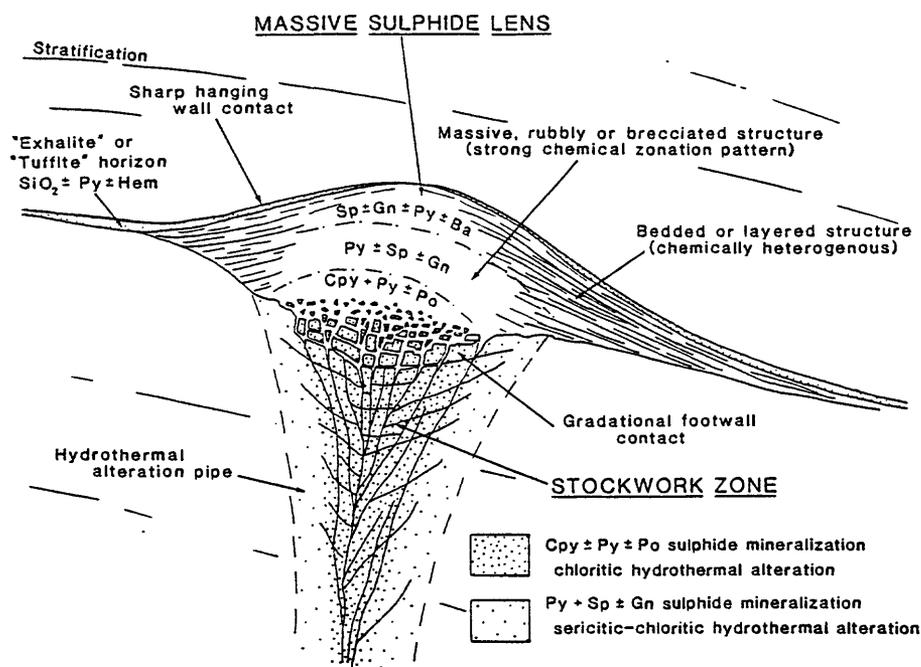


Figure 1. Essential characteristics of an idealized volcanogenic massive sulfide deposit (modified from Lydon, 1984). Mineral abbreviations as follows: Sp, sphalerite; Gn, galena; Py, pyrite; Ba, barite; Cpy, chalcopyrite; Po, pyrrhotite; and Hem, hematite.

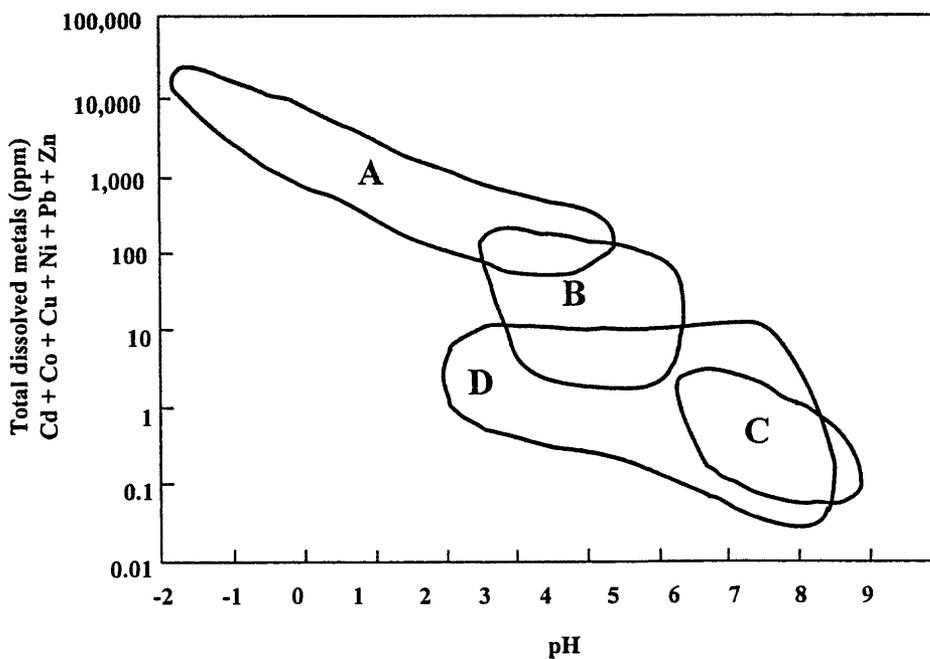


Figure 2. Ficklin plot (Plumlee and others, 1993) showing aqueous metal contents and pH ranges of water associated with volcanic massive sulfide deposits. Fields A, B, and C (Plumlee and others, 1994), are those for West Shasta, Calif., district VMS deposits, sulfide-mineral-rich vein deposits in rocks with low buffering capacity, and sulfide-mineral-rich vein deposits in carbonate host rocks, respectively. Field D is the composite field for water draining Prince William Sound, Alaska, VMS deposits (Goldfarb and others, in press).

Examples

Cyprus-type: Skouriotissa, Cyprus; Betts Cove, Newfoundland; Turner-Albright, Oreg.; Big Mike, Nev.

Kuroko-type: Kidd Creek, Ontario; Iron King and Penn Mine, Calif.; Mokuroko district, Japan.

Besshi-type: Besshi, Japan; Windy Craggy, British Columbia.

Spatially and (or) genetically related deposit types

VMS deposits are associated with a number of other mineral deposit types (Cox and Singer, 1986). Some VMS deposits, especially the Besshi-type deposits as broadly defined by Slack (1993), are transitional in depositional setting with some sedex deposits (Model 31a), such as Sullivan, British Columbia. VMS deposits are commonly associated with regionally developed iron- and (or) manganese-rich metalliferous sediment and chert developed at the same time-stratigraphic horizon as the massive sulfide deposits. Some Archean VMS deposits may be transitional to volcanic-associated iron formation. VMS deposits, especially in Archean terranes, tend to be spatially associated with shear-hosted mesothermal lode gold deposits (Model 36a) and Algoma-type banded iron formation (Model 28b).

Potential environmental considerations

Volcanic-associated massive sulfide deposits are among the most likely of all deposit types to have associated environmental problems, particularly acid mine drainage. Analyses of water draining VMS deposits plot in the extreme metal-extreme acidity field (fig. 2). VMS deposits have high iron- and base-metal-sulfide mineral contents and are hosted by rocks with low buffering capacity. These minerals are unstable under normal oxidizing near surface conditions and represent potential sources of highly acid and metal-rich drainage, especially in areas disturbed by surface mining or tailings disposal. Associated high abundances of potentially toxic trace metals, including arsenic, bismuth, cadmium, mercury, lead, and antimony, are present in some deposits, particularly those associated with felsic volcanic or sedimentary source rocks.

Exploration geophysics

Electrical properties of sulfide minerals, combined with large sulfide mineral concentrations in VMS deposits, make this type of mineral deposit a particularly favorable target for location by a variety of geophysical techniques. Self-potential, induced polarization, and a wide range of electromagnetic methods have been successfully used to locate buried VMS deposits. Pyrrhotite-rich and magnetite-bearing massive sulfide deposits may be locatable by detailed magnetic surveys. Airborne multispectral remote sensing techniques have been used to identify areas that contain hydrothermally altered rock and stressed vegetation that may be associated with mineralized rock.

References

Franklin and others (1981), Ohmoto and Skinner (1983), Fox (1984), Lydon (1984, 1988), Franklin (1993), and Slack (1993).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Historically, most economic deposits are in the 1-5 million tonnes range (Singer, 1986c,d; Singer and Mosier, 1986). Deposits of this size can still be developed in areas with an existing mining infrastructure; however, development of new deposits in frontier areas likely requires at least 10 million tonnes of reasonably high grade ore. Most Cyprus-type deposits contain less than 15 million tonnes of ore. Most Besshi-type deposits are also fairly small; notable exceptions include the >300 million tonne Windy Craggy, British Columbia, deposit. Kuroko-type deposits, especially those of Precambrian age, can be very large, such as the world class Kidd Creek, Ontario, deposit.

Host rocks

Cyprus-type deposits are hosted by submarine mafic-volcanic rocks and their altered equivalents, typically in brecciated rocks commonly associated with pillow lavas, which have good buffering capacity. Host-rocks for Kuroko-type deposits range from basalt to rhyolite, which have high and low buffering capacities, respectively. Many deposits are associated with subaqueous dacitic-domes that have intermediate buffering capacity. Host rocks are commonly brecciated and are typically moderately to highly altered. Some deposits are hosted by associated volcanoclastic or hemipelagic sedimentary rocks that overly submarine volcanic sequences. Besshi-type deposits are typically hosted by turbiditic to hemipelagic graywacke interbedded with or intruded by basalt.

Surrounding geologic terrane

Submarine volcanic activity is a defining characteristic of VMS deposits. Most VMS deposits, including many ophiolite-hosted deposits of the Cyprus-type, are associated with arc-related volcanism. Local extensional tectonic environments are particularly conducive to deposition of massive sulfide deposits. Many VMS deposits are in rocks that have undergone collisional tectonism and may be in structural contact with a wide variety of rock types.

Wall-rock alteration

Footwall alteration is moderate to locally intense around most VMS deposits. Hanging-wall alteration is typically absent, but may be weakly developed in some deposits. Many deposits that have not been tectonically disrupted are underlain by "stringer-zone" mineralized and altered rock. Stringer-zones are characterized by anastomosing quartz-sulfide veins. Local zones of silicification are present near and within mineralized zones. The most common alteration is pervasive chloritization, which is less well developed with increasing depth and distance from hydrothermal upwelling zones, in the footwall of deposits. Deposits hosted by felsic rocks typically have extensively developed quartz sericite alteration in the footwall. Most altered rock associated with massive sulfide deposits has low to very low acid buffering capacity. Some massive sulfide deposits are associated with pervasive carbonate alteration in the footwall (for instance, Sturgeon Lake, Ontario; Morton and others, 1990). These carbonate alteration zones typically have low to moderate abundances of calcitic to ankeritic carbonate minerals. Massive sulfide deposits with associated carbonate alteration assemblages that are easily accessible to acid water are less likely to produce acid drainage.

Nature of ore

Massive sulfide deposits, by definition, contain zones or lenses of massive sulfide minerals, many with sulfide mineral contents exceeding 90 volume percent. Most deposits also contain extensive zones of semi-massive sulfide rock (25 to 50 volume percent) that contain economically exploitable ore. Stringer zone ore zones typically contain 5 to 20 volume percent sulfide minerals, hosted in quartz veins and disseminated in chloritic wall rocks. Disseminated sulfide rock is extensively developed in footwall alteration zones; sulfide mineral abundances decrease with depth below the massive sulfide zone horizon. Lateral development of disseminated pyrite can be continuous for large distances at and immediately below the stratigraphic horizon of the massive sulfide lens.

Deposit trace element geochemistry

Iron is nearly always the predominant metal in sulfide phases. Economically exploitable VMS deposits associated with mafic rocks are variably enriched in copper and zinc, whereas those that contain a significant component of

felsic volcanic or sedimentary rock are relatively enriched in zinc and lead. Deposits associated with mafic rocks can contain anomalous concentrations of gold, silver, and cobalt. Deposits associated with felsic volcanic and sedimentary rocks contain minor to significant concentrations of lead, silver, arsenic, antimony, cadmium, and locally bismuth, tin, and selenium.

Ore and gangue mineralogy and zonation

The dominant sulfide mineral in most VMS deposits is pyrite, but pyrrhotite is dominant in others. Marcasite, which is present either intergrown with fine grained pyrite or as a replacement product of pyrrhotite, is generally a minor constituent but can constitute a potential source of acidic drainage because of its high reactivity relative to pyrite. The other dominant phases include sphalerite and chalcopyrite, accompanied by galena in VMS deposits associated with felsic rock. Other ore minerals are present in much lower abundances, but constitute important potential heavy metal sources. The most common accessory sulfide and sulfosalt minerals are those of the tennantite-tetrahedrite series, arsenopyrite, and various lead-antimony-bismuth sulfosalt minerals, particularly in deposits associated with felsic rock. Deposits associated with mafic rock may contain cobalt sulfide or thiospinel. Magnetite is present in some deposits and barite can be very abundant in Kuroko-type VMS deposits, in which it commonly forms an important ore facies. Gypsum and anhydrite are also abundant in some Kuroko deposits. The most common silicate gangue minerals are quartz and chlorite, which are accompanied by sericite in deposits associated with felsic rocks. Other gangue phases are much less abundant, except in massive sulfide deposits that have been metamorphosed to greenschist or higher metamorphic grades. In these metamorphosed deposits, phases such as anthophyllite and cordierite form from chloritic protoliths.

Metal zoning is well developed in massive sulfide deposits. Copper abundances are elevated in footwall and stringer ore zones, and zinc content increases upward and outward from the core of hydrothermal upwelling zones. In felsic-associated deposits, lead, arsenic, and antimony abundances are enriched upward and outward from the zinc-rich zones. Barite and silica are also enriched toward the stratigraphic tops and distal edges of most Kuroko-type deposits.

Mineral characteristics

Grain size is highly variable and is generally controlled by primary sulfide mineralogy and the extent of metamorphic recrystallization. Primary sulfide minerals of most zinc-lead-copper deposits are fine grained and intergrown, whereas those of most copper-zinc deposits are coarser grained (Franklin, 1993). The extent of grain size changes depends upon pressure and temperature conditions attained during metamorphism, and on the ductility of sulfide minerals. For example, cataclastic deformation significantly reduces grain-size and therefore reactivity of brittle sulfide minerals such as chalcopyrite and pyrite, but plastically deforms ductile sulfide minerals such as galena. Thermal metamorphism commonly causes sulfide ore to become much coarser grained and develop mosaic or porphyroblastic sulfide textures (Stanton, 1972).

Secondary mineralogy

Both initial seafloor and later near surface oxidation of massive sulfide minerals results in the formation of iron-rich gossan. Intermediate stages of oxidation also can result in the formation of a wide range of iron- and base-metal sulfate and sulfate-hydrate minerals. These highly soluble minerals are potentially important reservoirs of heavy metals that can be easily mobilized and potentially can produce high peak loads of dissolved metals if hydrologic conditions are suddenly altered, for example, by surface mining of a deposit in a wet climate. Secondary minerals formed in temperate climates include goethite, crystalline and amorphous silica, jarosite, a variety of metal-bearing hydroxy-sulfate minerals (beudantite, plumbojarosite, argentojarosite, woodhouseite, beaverite, meta-aluminite, hinsdalite, and brochantite), scorodite, native gold, native silver, native bismuth, barite, anglesite, litharge, covellite, chalcocite, digenite, enargite, luzonite, and acanthite.

Topography, physiography

These deposits have no specific topographic or physiographic features.

Hydrology

These deposits exert no specific influence on the adjacent hydrologic regime, partly because of their relatively small size. The extent of mineralized outcrop and (or) mine-related excavations exposed to the atmosphere or oxidized groundwater, and their position relative to the water table, are hydrologic factors that can significantly influence the

intensity and scale of environmental problems related to VMS deposits. Availability of oxidizing water is a controlling factor for acid generating potential and dissolved metal carrying capacity of water interacting with massive sulfide deposits or their mine-related products.

Mining and milling methods

Mining methods have a large influence on the potential environmental impacts of massive sulfide deposits. Both open-pit and underground methods have been used to mine VMS deposits in historic and modern operations. Local climatic and hydrologic conditions influence the acid generating capacity of deposits. Most massive sulfide deposits contain a large excess of iron-sulfide minerals relative to valuable base-metal sulfide minerals. The nature of ore processing and the method of deposition of the sulfide-mineral-rich tailings and waste rocks are critical parameters that influence the scope of environmental impacts associated with mining massive sulfide deposits. Fine-grained and intergrown sulfide minerals may require very fine grinding, which can result in highly reactive tailings, for beneficiation. Many modern mines discharge fine-grained sulfide-mineral-rich tailings into surface tailings ponds underlain by a number of impermeable linings. Previous mining operations often discharged tailings in a manner that resulted in significant contamination of surface and shallow ground water. Some active underground mines are able to dispose of essentially all tailings by backfilling and cementing mined stopes; consequently, surface contamination is virtually eliminated. Base-metal sulfide minerals are typically separated by flotation; some surfactants used in the process are toxic. Most of these surfactants are recycled and relatively minor amounts are discharged to tailings ponds.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Natural drainage water: Published data concerning the chemistry of natural drainage associated with VMS deposits include: Goldfarb and others (in press), Prince William Sound, Alaska; Greens Creek Environmental Impact Statement (1983), Admiralty Island, Alaska; and Filipek and others (1987), West Shasta, Calif., district. Temperate rainforest climate--Water draining Cyprus- and Besshi-type VMS deposits in the Prince William Sound area is dilute calcium-bicarbonate-type water (5.8 mg/l Ca and 15 mg/l HCO_3^-) that is slightly acidic to neutral (pH 6.4 to 7.6); the type of host rock, sedimentary or volcanic, does not seem to affect these generalizations. Specific conductance is <50 uS/cm. Metal abundances in this water include 20 $\mu\text{g/l}$ iron, 15 $\mu\text{g/l}$ aluminum, <2 $\mu\text{g/l}$ arsenic, 1.4 $\mu\text{g/l}$ zinc, and <1 $\mu\text{g/l}$ silver, copper, cobalt, chromium, lead, molybdenum, and antimony. Stream water flowing over undisturbed mineralized rock above several deposits has slightly elevated metal abundances, including as much as 40 $\mu\text{g/l}$ iron, 2 $\mu\text{g/l}$ copper, and 52 $\mu\text{g/l}$ zinc; pH varies from 5.6 to 7.3. Montaine, semi-arid climate--Natural water draining unmineralized areas above the West Shasta district (Filipek and others, 1987) also is calcium bicarbonate-type water (14 mg/l calcium and 22 mg/l HCO_3^-) that has a pH of 6.15 and a specific conductance of 100 uS/cm. This water contains 8 mg/l iron, 18 mg/l aluminum, <12 mg/l copper, <10 mg/l zinc, and <1 mg/l arsenic.

Mine drainage water: Published data sources concerning the chemistry of mine drainage associated with VMS deposits include: Goldfarb and others (in press), Beatson and eight other mines in Prince William Sound, Alaska; Kilburn and others (1994, 1995), Holden mine, Wash.; Alpers and others (1991), Penn mine, Calif.; and Alpers and others (1991, 1994), Iron Mountain mine, Calif. Temperate rainforest climate--The most acidic and metal-rich mine water, draining from the base of well consolidated tailings piles of Besshi-type deposits, from two locations in the Prince William Sound, Alaska, has a pH of 2.6 to 2.7 and contains as much as 21,000 $\mu\text{g/l}$ iron, 3,600 $\mu\text{g/l}$ copper, 220 $\mu\text{g/l}$ lead, 3,300 $\mu\text{g/l}$ zinc, 30 $\mu\text{g/l}$ cobalt, 10 $\mu\text{g/l}$ cadmium, and 311 mg/l sulfate. The tailings are devoid of vegetation and the drainages support a rich growth of bright green, copper-loving, bryophyte algal mats. Slightly acidic (pH 4.3 to 6.6) mine water was identified at six other deposits. Maximum metal values are 310 $\mu\text{g/l}$ iron, 1,400 $\mu\text{g/l}$ copper, and 3,100 $\mu\text{g/l}$ zinc. Kilburn and others (1994) sampled acidic mine drainage from within adits and below consolidated tailings piles at the Holden Mine, a copper-zinc VMS in amphibolitic mafic volcanic rocks. Water within the adits has a pH of about 5 and metal concentrations of 370-580 $\mu\text{g/l}$ iron, 570-580 $\mu\text{g/l}$ copper, and nearly 5,000 $\mu\text{g/l}$ zinc. Effluent from tailings piles has a pH of 2.8 to 2.9 and contains 23,000 to 50,000 $\mu\text{g/l}$ iron, 21 to 53 $\mu\text{g/l}$ copper, and 130 to 3,800 $\mu\text{g/l}$ zinc. Montaine, semi-arid climate--The Iron Mountain mine contains the most acidic and metal-rich mine water ever recorded. Alpers and Nordstrom (1991) have reported pH values ranging between 1.5 and <-1.0. The first ever occurrence of pH values less than one were obtained for dripping mine water that was actively precipitating melanterite and other efflorescent metal-sulfate salts. This water contains as much as 11 weight percent iron, 2.3 weight percent zinc, 0.5 weight percent copper, and 76 weight percent sulfate, with 340 mg/l arsenic, 211 mg/l cadmium, 12 mg/l lead, and 29 mg/l antimony.

Metal mobility from solid mine wastes

Soluble sulfate salt minerals derived from weathering and oxidation of sulfide minerals in mine dumps and tailings piles represent a potential source of metal contamination and acid generation. As percolating surface and ground water evaporates during dry periods, efflorescent metal-sulfate salt minerals form encrustations around and below the base of the piles, which effectively stores acidity and metals released during sulfide mineral breakdown. Subsequent rainfall or snowmelt following a dry period is likely to release a highly concentrated pulse of acid mine water. Mine dumps associated with lead-rich VMS deposits (Kuroko-type) may be a source of lead contamination due to high concentrations of soluble secondary lead minerals.

Secondary minerals in tailings impoundments include a variety of iron oxyhydroxides (goethite, lepidocrocite, akaganeite, maghemite, and ferrihydrite), sulfates (gypsum, bassanite, jarosite, hydronium jarosite, melanterite, goslarite, ferrohexahydrite, epsomite, hexahydrite, siderotil, rozenite, anglesite, alunogen, and copiapite), and minerals such as marcasite, covellite, and native sulfur (Jambor, 1994). Pore water from tailings impoundments associated with the Heath Steele, New Brunswick, deposit are acidic (pH 1.8 to 5.2), have Eh of 280 to 580 mV, and contain significant dissolved metal abundances, including 0.3 to 600 mg/l copper, 0.8 to 11 mg/l lead, 23 to 4,880 mg/l zinc, 1,200 to 36,000 mg/l iron, and 600 to 67,600 mg/l sulfate (Boorman and Watson, 1976). Similarly, pore water from tailings impoundments associated with the Waite Amulet, Quebec, deposit are acidic (pH 2.5 to 6.0), have Eh of 200 to 700 mV, and contain significant dissolved metal abundances, including as much as 65 mg/l copper, as much as 5 mg/l lead, as much as 250 mg/l zinc, as much as 8,000 mg/l iron, and as much as 20,000 mg/l sulfate (Blowes and Jambor, 1990). Finally, pore water from tailings impoundments associated with the Kidd Creek, Ontario, deposit are acidic (pH 3.5 to 7.5), have Eh of 50-500 mV, and contain significant dissolved metal abundances, including 0 to 38 mg/l copper, 0 to 2 mg/l lead, 0 to 6,200 mg/l zinc, 0 to 350 μ g/l arsenic, 1 to 990 mg/l iron, and 1,860 to 27,000 mg/l sulfate (Al and others, 1994).

Extremely fine grinding required for beneficiation of VMS ore may enhance airborne transport of lead-arsenic-cadmium-antimony-bearing dust. This phenomenon is most probable in semi-arid to arid regions in which strong winds prevail.

Soil, sediment signatures prior to mining

The elemental suite and magnitude of geochemical anomalies in soil and sediment collected from undisturbed VMS deposits depend upon a number of factors, including VMS deposit type, extent of ore outcrop or overburden, climate, topography, etc. Stream sediment samples collected below Kuroko-type deposits in temperate rain forest on Admiralty Island, Alaska, contain 5 to 10 weight percent iron, as much as 10,000 ppm barium, hundreds to several thousand ppm zinc, hundreds of ppm lead, tens to hundreds of ppm arsenic, copper, and nickel, as well as 0 to 20 ppm silver, bismuth, cadmium, mercury, molybdenum, and antimony (Kelley, 1990; Rowan and others, 1990; Taylor and others, 1992; C.D. Taylor, unpub. data, 1995).

Stream sediment geochemical signatures associated with undisturbed to variably disturbed Cyprus and Besshi VMS deposits in the Prince William Sound, Alaska, are similar to those just described. They contain 10 to 40 weight percent iron, several hundred ppm barium, hundreds of ppm arsenic and zinc, tens to hundreds of ppm lead, hundreds to thousands of ppm copper, and 0 to 20 ppm silver, bismuth, mercury, molybdenum, and antimony (R.J. Goldfarb, unpub. data, 1995).

Potential environmental concerns associated with mineral processing

Tailings ponds below mills are likely to contain high abundances of lead, zinc, cadmium, bismuth, antimony, and cyanide and other reactants used in flotation and recovery circuits. Highly pyritic-pyrrhotitic orebodies that are exposed to oxidation by air circulating through open adits, manways, and exploration drill holes may evolve SO₂ gas; in some cases, spontaneous combustion can cause sulfide ore to burn. Tailings that contain high percentages of non-ore iron sulfide minerals have extremely high acid-generating capacity. Surficial stockpiles of high-sulfide mineral ore are also potential sources of metal-rich mine water.

Smelter signatures

Most base-metal rich ore concentrates are smelted. In most cases, concentrates are shipped to custom smelters, and therefore do not contribute to the environmental impact in the immediate mine vicinity. Larger districts are often served by a smelter co-located in the district. Data compiled by Gulson and others (1994) document the relationship between lead in soil near smelters and blood lead in children; similar data for the Leadville, Colo., area indicate similar trends. Additional data may be available for the Trail, British Columbia and El Paso, Tex. smelters.

Climate effects on environmental signatures

Great differences between geochemical mine drainage data for deposits in the West Shasta, Calif., district, eastern Canada, and that for deposits in cooler and wetter Alaskan climates underscore the important role of climate with regard to acid mine drainage associated with VMS deposits. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell. In wet climates, high water tables may reduce exposure of abandoned orebodies to oxidation and continually flush existing tailings and mine dumps. Although metal-laden acid mine water does form, it is may be diluted to benign metal abundances within several hundred meters of mixing with a higher order stream.

Geoenvironmental geophysics

Self potential detects electrical potentials produced by ongoing redox reactions. The method is suitable for locating "hot spots" in tailings piles. Electromagnetic surveys are useful for tracing and monitoring metal-bearing ground water. In addition, detailed magnetic data can help delineate geologic contacts, strata, and fractures that may act as fluid conduits, especially in crystalline rocks.

REFERENCES CITED

- Al, T.A., Blowes, D.W., and Jambor, J.L., 1994, A geochemical study of the tailings impoundment at the Falconbridge Limited, Kidd Creek division metallurgical site, Timmons, Ontario, *in* Jambor, J.L., and Blowes, D.W. eds., Short Course Handbook on Environmental Geochemistry of Sulfide Mine-wastes, Mineralogical Association of Canada, v. 22, p. 333-364.
- Alpers, C.N., and Nordstrom, D.K., 1991, Geochemical evolution of extremely acid mine waters at Iron Mountain, California--Are there any lower limits to pH?, *in* Proceedings, Second International Conference on the Abatement of Acidic Drainage: MEND (Mine Environmental Neutral Drainage), Ottawa, Canada, v. 2, p. 321-342.
- Alpers, C.N., Nordstrom, D.K., and Thompson, J.M., 1994, Seasonal variations of Zn/Cu ratios in acid mine waters from Iron Mountain, California, *in* Alpers, C.N., and Blowes, D.W., eds., Environmental geochemistry of sulfide oxidation, ACS Symposium Series 550: Washington D.C., American Chemical Society, p. 324-344.
- Blowes, D.W., and Jambor, J.L., 1990, The pore-water geochemistry and the mineralogy of the vadose zone of sulfide tailings, Waite Amulet, Quebec, Canada: Applied Geochemistry, v. 5, p. 327-346.
- Boorman, R.S., and Watson, D.M., 1976, Chemical processes in abandoned sulphide tailings dumps and environmental implication for northeastern New Brunswick, Canadian Institute of Mining and Metallurgy Bulletin, v. 69, no. 772, p. 86-96.
- Cox, D.P., 1986, Descriptive model of Besshi massive sulfide, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 136.
- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- Filipek, L.H., Nordstrom, D.K., and Ficklin, W.H., 1987, Interaction of acid mine drainage with waters and sediments of West Squaw Creek in the West Shasta mining district, California: Environmental Science and Technology, v. 21, no. 4, p. 388-396.
- Fox, J.S., 1984, Besshi-type volcanogenic sulphide deposits--a review, Canadian Institute of Mining and Metallurgy Bulletin, v. 77, no. 864, p. 57-68.
- Franklin, J.M., 1993, Volcanic-associated massive sulphide deposits, *in* Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., and Duke, J.M., eds., Mineral deposit modeling, Geological Association of Canada Special Paper 40, p. 315-334.
- Franklin, J.M., Sangster, D.M., and Lydon, J.W., 1981, Volcanic-associated massive sulfide deposits, *in* Skinner, B.J., ed., Economic Geology 75th anniversary volume, p. 485-626.
- Goldfarb, R.J., Nelson, S.W., Taylor, C.D., d'Angelo, W.M., and Meier, A.L., in press, Acid mine drainage associated with volcanogenic massive sulfide deposits, Prince William Sound, Alaska, *in* Dumoulin, J.A., and Moore, T.E., eds., Geologic studies in Alaska by the U.S. Geological Survey, 1994: U.S. Geological Survey Bulletin 2152.
- Greens Creek Environmental Impact Statement, 1983.

- Gulson, B.L., Mizon, K.J., Law, A.J., Korsch, M.J., Davis, J.J., and Howarth, D., 1994, Source and pathways of lead in humans from the Broken Hill mining community--An alternative use of exploration methods: *Economic Geology*, v. 89, p. 889-908.
- Jambor, J.L., 1994, Mineralogy of sulfide-rich tailings and their oxidation products, *in* Jambor, J.L. and Blowes, D.W., eds., *Short Course Handbook on Environmental Geochemistry of Sulfide Mine-wastes: Mineralogical Association of Canada*, v. 22, p. 59-102.
- Kelley, K.D., 1990, Interpretation of geochemical data from Admiralty Island, Alaska--Evidence for volcanogenic massive sulfide mineralization, *in* Goldfarb, R.J., Nash, J.T., and Stoeser, J.W., eds., *Geochemical studies in Alaska by the U.S. Geological Survey, 1989*, U.S. Geological Survey Bulletin 1950, p. A1-A9.
- Kilburn, J.E., Sutley, S.J., and Whitney, G.C., 1995, Geochemistry and mineralogy of acid mine drainage at the Holden mine, Chelan County, Washington: *Explore*, Association of Exploration Geochemists newsletter, no. 87, p. 9-14.
- Kilburn, J.E., Whitney, G.C., d'Angelo, W.M., Fey, D.L., Hopkins, R.T., Meier, A.L., Motooka, J.M., Roushey, B.H., and Sutley, S.J., 1994, Geochemical data and sample locality maps for stream sediment, heavy-mineral-concentrate, mill tailing, water, and precipitate samples in and around the Holden mine, Chelan County, Washington: U.S. Geological Survey Open-File Report 94-680A, 33 p.
- Lydon, J.W., 1984, Volcanogenic massive sulphide deposits, Part 1--A descriptive model: *Geoscience Canada*, v. 11, p. 195-202.
- _____ 1988, Volcanogenic massive sulphide deposits, Part 2--Genetic models: *Geoscience Canada*, v. 15, p. 43-65.
- Morton, R.L., Hudak, G., Walker, J., and Franklin, J.M., 1990, Physical volcanology and hydrothermal alteration of the Sturgeon Lake caldera complex, *in* Franklin, J.M., Schneiders, B.R., and Koopman, E.R., eds., *Mineral Deposits in the western Superior province, Ontario: Geological Survey of Canada, Open File 2164*, p. 74-94.
- Ohmoto, H., and Skinner, B.J., 1983, The Kuroko and related volcanogenic massive sulfide deposits: *Economic Geology Monograph* 5, 604 p.
- Plumlee, G.S., Smith, K.S., Ficklin, W.H., Briggs, P.H., and McHugh, J.B., 1993, Empirical studies of diverse mine drainages in Colorado: Implications for the prediction of mine-drainage chemistry: *Proceedings, 1993 Mined Land Reclamation Symposium*, Billings, Montana, v. 1, p. 176-186.
- Plumlee, G.S., Smith, K.S., and Ficklin, W.H., 1994, Geoenvironmental models of mineral deposits, and geology-based mineral-environmental assessments of public lands: U.S. Geological Survey Open-File Report 94-203, 7 p.
- Rowan, E.L., Bailey, E.A., and Goldfarb, R.J., 1990, Geochemical orientation study for identification of metallic mineral resources in the Sitka quadrangle, southeastern Alaska, *in* Goldfarb, R.J., Nash, J.T., and Stoeser, J.W., eds., *Geochemical studies in Alaska by the U.S. Geological Survey, 1989*, U.S. Geological Survey Bulletin 1950, p. B1-B12.
- Singer, D.A., 1986a, Descriptive model of Cyprus massive sulfide, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin* 1693, p. 131.
- _____ 1986b, Descriptive model of Kuroko massive sulfide, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin* 1693, p. 189-190.
- _____ 1986c, Grade and tonnage model of Cyprus massive sulfide, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin* 1693, p. 131-135.
- _____ 1986d, Grade and tonnage model of Besshi massive sulfide, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin* 1693, p. 136-138.
- Singer, D.A., and Mosier, D.L., 1986, Grade and tonnage model of Kuroko massive sulfide, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin* 1693, p. 190-197.
- Slack, J.F., 1993, Descriptive and grade-tonnage models for Besshi-type massive sulfide deposits, *in* Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., and Duke, J.M., eds., *Mineral deposit modeling*, Geological Association of Canada Special Paper 40, p. 343-372.
- Stanton, R.L., 1972, *Ore Petrology*, McGraw-Hill, New York, 713 p.
- Taylor, C.D., Cieutat, B.A., and Miller, L.D., 1992, A followup geochemical survey of base metal anomalies in the Ward Creek/Windfall Harbor and Gambier Bay areas, Admiralty Island S.E. Alaska, *in* Bradley, D., and Dusel-Bacon, C., eds., *1991 Geologic Studies in Alaska: U.S. Geological Survey Bulletin* 2041, p. 70-85.

BLACKBIRD CO-CU DEPOSITS (MODEL 24d; Earhart, 1986)

by Karl V. Evans, J. Thomas Nash, William R. Miller, M. Dean Kleinkopf, and David L. Campbell

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

These deposits are stratabound iron-, cobalt-, copper-, and arsenic-rich sulfide mineral accumulations in nearly carbonate-free argillite/siltite couplets and quartzites with minor acid-consuming capacity; deposits have high acid-generating capacity.

Examples

Idaho cobalt belt, especially Blackbird Mine, Idaho.

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include Besshi massive sulfide deposits (Model 24b).

Potential environmental considerations

- (1) Most ore is sulfide-mineral rich and contains almost no carbonate minerals. Host rocks are meta-clastic and have limited acid-buffering capacity. Locally, minor buffering capacity is provided by siderite gangue.
- (2) Very high potential for generation of acid (pH 2 to 3) drainage with thousands of mg/l copper and sulfate, hundreds of mg/l cobalt and iron, tens of mg/l aluminum, hundreds of $\mu\text{g/l}$ zinc, and tens of $\mu\text{g/l}$ arsenic. After mining operations have ended, sulfide minerals in waste rock and tailings piles may continue to oxidize and produce acid drainage with elevated metal contents.
- (3) If fractured host-rock allows oxygenated water to infiltrate underground sulfide ore and old mine workings, acid mine drainage generation may continue after mining is complete. Non-point source emission of acid water at surface seeps is both a known (Baldwin and others, 1978; Reiser, 1986) and potential hazard.
- (4) Potential downstream environmental effects of acid drainage can be significant in spatial extent, especially if surrounding terrane is, as at Blackbird, dominantly quartzo-feldspathic meta-clastic strata and granite with low acid-buffering capacity. Downstream water can be highly acidic and contain elevated concentrations of copper, cobalt, iron, and, depending on pH, arsenic.
- (5) Environmental mitigation should focus on isolating sulfide-mineral-bearing rock, especially that in easily oxidized waste-rock piles, from water and oxygen. Rerouting drainages around mine sites would reduce the quantity of water that required treatment.

Exploration geophysics

Various satellite and airborne multispectral remote sensing techniques can be used to identify alteration mineral assemblages and stressed vegetation sites. Purdy and others (1986) made a preliminary evaluation of stressed vegetation in the Blackbird mine area. They demonstrated that Englemann spruce and lodgepole pine growing in soil enriched in cobalt and copper had higher spectral reflectance, as measured by a field-portable spectroradiometer, than the same species growing in background areas. At the time of their study, they were unable to detect these differences using Landsat Thematic Mapper data, probably because of noise from canopy density variations and strong topographic control of tree distribution. More recently developed remote sensing technology may be able to identify the stressed vegetation whose presence Purdy and others (1986) identified in the Blackbird area.

In the vicinity of the Idaho cobalt belt, aeromagnetic methods may be the most useful geophysical method in regional exploration for cobalt-copper deposits. The Blackbird mine lies on the southwest flank of a prominent magnetic trough that parallels the Idaho cobalt belt (Lund and others, 1990). This trough may indicate a structural or lithologic zone that is relatively depleted of magnetite. However, the oxide zone (see below for discussion of this zone) lies stratigraphically below the Blackbird mine, and is characterized by enrichments of copper, cobalt, and magnetite. Connor (1991) used existing aeromagnetic data to suggest potential extensions of the oxide zone to the southeast of his study area. However, Tertiary and lower Paleozoic plutons impose strong control on regional aeromagnetic patterns (Lund and others, 1990), which indicates the need for care in making regional interpretations. Detailed surveys tied to similarly detailed ground control are probably needed to better define a geophysical exploration strategy for cobalt-copper deposits of the Blackbird type.

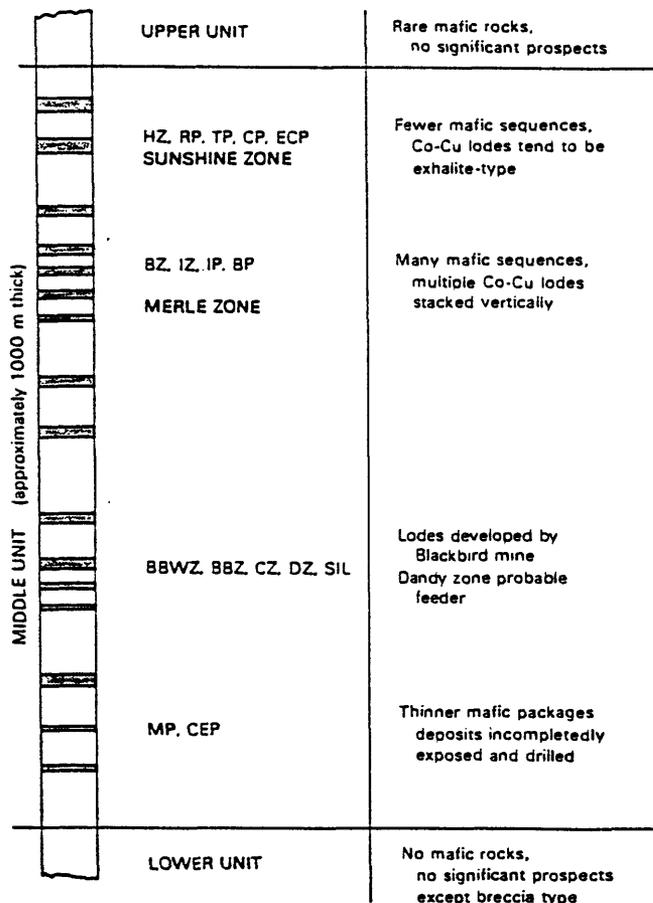


Figure 1. Schematic section of mafic rock-rich (biotite-rich) sequences and associated Co-Cu lodes in the middle unit of the Yellowjacket Formation in the Blackbird mine area. Abbreviations are for lodes and prospects (see Nash and Hahn, 1989, for key and further information). From Nash and Hahn (1989).

References

Geology: Bennett (1977), Nash and Hahn (1989), Nash and Connor (1993), and Evans (in press).
Environmental geology, geochemistry: Baldwin and others (1978), Reiser (1986), McHugh and others (1987), and Desborough (1994).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

These deposits are of small to intermediate size. Blackbird mine has about 12 million tonnes of combined mining and indicated reserves (Nash and Hahn, 1989). Available data (generally from unpublished sources) suggest that other known deposits in the Idaho cobalt belt are smaller than Blackbird, although none of these deposits have been as extensively explored as Blackbird.

Host rocks

Host rocks for these deposits are quartzo-feldspathic siltite-argillite couplets and quartzite intercalated with significant proportions of biotite (biotite-dominant rock) (fig. 1). Biotite probably formed either as a volcanogenic mafic tuff or as a chemical sediment.

Surrounding geologic terrane

The area surrounding the Idaho cobalt belt is primarily underlain by non-calcareous Middle Proterozoic quartzite, siltite, and argillite, Middle Proterozoic granite, and Eocene Challis Volcanic Group rocks (Evans and Zartman, 1990;

Evans, in press). These rocks have limited acid mine drainage buffering capacity.

Wall-rock alteration

Alteration is stratabound and coextensive with ore (Nash and Hahn, 1989). The transition from altered to unaltered rock is abrupt (<1 m) in many places. Altered rock in the Merle ore zone (fig. 1) at Blackbird is coincident with biotitite and intercalated rocks and contains elevated abundances of cobalt and arsenic. Alteration zoning consists of pyrite-siderite-quartz-muscovite in the core zone and grades outward into quartz-muscovite-(with lesser) pyrite. Potassic alteration has enhanced biotite crystallization across the entire ore zone. Acid mine drainage that encounters siderite is somewhat buffered; finer grained siderite has greater buffering capacity. Highly acidic water draining the Blackbird mine suggests that the buffering capacity of siderite is overwhelmed by acid-producing ore minerals.

Nature of ore

Deposits are closely associated with stratiform biotitites in the upper middle and lower upper stratigraphic units of the Yellowjacket Formation (Evans, in press). Other related, but smaller deposits include cobaltiferous-pyrite with variably abundant chalcopyrite that are associated with bedded magnetite in the lower Yellowjacket (oxide zone of Nash, 1989 and Nash and Connor, 1993; Jackass zone of Evans, in press), and relatively minor cobalt-bearing tourmaline breccias in the lower and middle units of the Yellowjacket (Modreski and Connor, 1991). Ore at Blackbird is both massive and disseminated. Fine- to very fine grained cobaltite and coarse-grained chalcopyrite dominate. Pyrite is erratically distributed at the deposit scale, but generally is present as coarse-grained crystals with chalcopyrite. Fine-grained pyrrhotite is present as cores in some concentrically banded pyrite crystals, but is most abundant in the probable feeder zone (Dandy zone) to the deposit.

Deposit trace element geochemistry

Blackbird mine: Co, Cu, Au, Fe, As, Bi, Cl, Cr, Mg, P, Sc, Ti, V, Y, Yb

Oxide zone: Fe, Cu, Sb, As, Au, Ba, Pb, Se, Zn, Co.

Complete analytical data for 372 samples of unoxidized drill core are available for several deposits in the Blackbird mine area (Nash and others, 1988). The following are ranges defined by the 10th and 90th percentile values and the means (in parentheses) for metals of particular interest. All values are in parts per million (ppm) unless otherwise indicated; nd indicates mean was not calculated because of strongly skewed data.

Fe: 6.6-18 (11.0) weight percent; S: <0.1-3.8 (0.2) weight percent; CO₂: <0.1-1.3 (0.2) weight percent; Ag: <1-1.5 (nd); As: 7-9,450 (130); Bi: <10-45 (nd); Cd: <1-<2 (nd); Co: 37-7,900 (180); Cr: 22-170 (46); Cu: 8-5,000 (250); Mo: <1-5 (nd); Ni: 10-380 (33); Pb: 2-15 (2.8); Se: <0.1-19 (9); Th: 5-19 (11); Zn: 14-62 (27).

Ore in the Blackbird mine area and associated alteration zones generally have very high abundances of iron, arsenic, cobalt, and copper; moderate to low sulfur in sulfide minerals; and relatively low to very low abundances of carbonate, silver, cadmium, chromium, molybdenum, nickel, lead, selenium, and zinc compared to other base-metal deposits.

Oxide zone deposits generally have abundances in the ranges suggested for deposits at Blackbird (Nash, 1989; Connor, 1991). Trace element environmental effects of oxide zone deposits are similar to those of Blackbird mine rocks, primarily due to the presence of acid-generating chalcopyrite and cobaltiferous pyrite.

Ore and gangue mineralogy and zonation

Potentially acid-generating minerals underlined. Blackbird mine (fig. 2): Major ore minerals-cobaltite, chalcopyrite, pyrite, pyrrhotite, native gold. Less abundant ore minerals and gangue-siderite, biotite, garnet, chloritoid, tourmaline, muscovite, arsenopyrite, linnaeite, safflorite, ±native silver, ±enargite, ±sphalerite, ±galena.

Distal deposits in Blackbird stratigraphic zone: Major ore minerals-pyrite, chalcopyrite, arsenopyrite, ±cobaltite. Oxide zone: Major ore minerals-cobaltiferous pyrite, magnetite, hematite, chalcopyrite, arsenopyrite. Less abundant ore minerals and gangue-marcasite, pickeringite, chalcantite.

Mineral characteristics

Blackbird mine: Cobaltite is present in very fine grained layers and thin stringers. Chalcopyrite is present in coarsely crystalline stringers and aggregates commonly enveloping cobaltite. Pyrite is coarsely crystalline, has internal concentric banding, and some contains fine-grained pyrrhotite cores.

Oxide zone: Pyrite is present in four forms: (1) fine-grained euhedral crystals interlaminated with argillite, (2) coarse-grained crystals, which form beds and cross-cutting structures, that enclose euhedral pyrite, (3) anhedral pyrite, which formed late in the paragenesis and encloses earlier crystals, and (4) corroded pyrite with a porous texture, probably

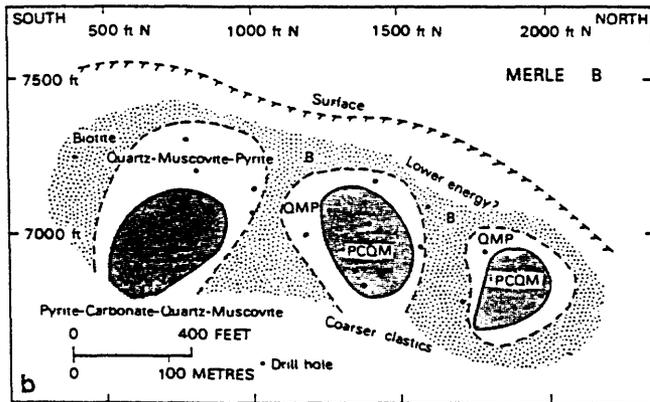
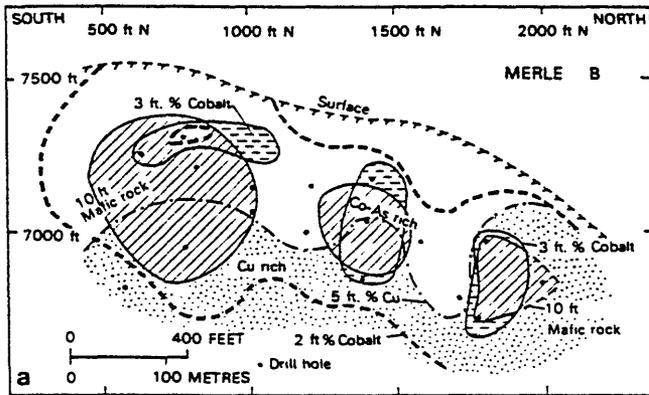


Figure 2. Schematic diagram of zoning in the Merle B lode, Blackbird mine. These longitudinal sections are essentially the same as plan maps of the originally subhorizontal lode. *A*, Zones of thickest mafic rock (biotitite) and richest concentrations of Co, As, and Cu expressed as feet/percent. *B*, Zones of gangue minerals pyrite (originally pyrrhotite), carbonate, quartz, and muscovite; biotite is present throughout the lode. From Nash and Hahn (1989).

indicating original precipitation as pyrrhotite. Some pyrite contains 2 to 4.5 weight percent cobalt; bismuth, lead, and zinc may also reside in the crystal lattice of pyrite. Chalcopyrite forms coarse-grained layers and cross-cutting structures that commonly surround pyrite. Magnetite is present in trace to major amounts as small, euhedral grains with very low cobalt content and <0.02 weight percent TiO_2 . Magnetite grains form beds, with no evidence of a detrital origin, that may have formed by chemical sedimentation.

Secondary mineralogy

Secondary minerals include pickeringite, chalcantite, malachite, azurite, limonite, and erythrite(?).

Topography, physiography

In the Blackbird region, topography is that of a deeply incised plateau with steep-walled canyons. Biotitite-rich strata weather easily and even quartzo-feldspathic strata tend to produce rubble and talus rather than prominent outcrops.

Hydrology

Most precipitation near Blackbird falls during the Winter. Baldwin and others (1978) indicate a seven-year average of about 124 cm of snow with a water content of about 38 cm. Streamflow peaks during Spring runoff (April through June) and falls to very low levels in late Summer and early Autumn. Highly fractured Yellowjacket Formation at Blackbird mine permits rapid correlated recharge and discharge of ground water. During the early part of the Spring runoff, drainage through acid-producing mine workings and waste rock/tailings piles flushes large quantities of soluble salts containing metals and acidity into surface drainages.

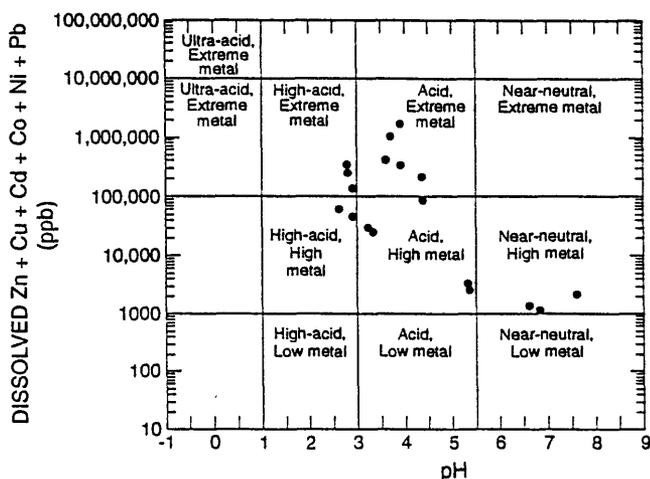


Figure 3. Ficklin plot (Plumlee and others, 1993; Smith and others, 1994) of pH versus the sum of dissolved base metals Zn, Cu, Cd, Co, Ni, and Pb in mine and natural water draining waste rock in the Meadow Creek/Blackbird Creek and Bucktail Creek drainages at Blackbird mine. Values shown are from water most closely associated with sources of acid mine drainage at Blackbird mine. Available data do not include analyses for all base metals summed in the diagram; therefore data points are minimum values. Data from Baldwin and others (1978) and McHugh and others (1987).

Mining and milling methods

Underground mining at Blackbird was from drifts following lenticular and tabular orebodies using room and pillar methods and block caving of overhead stopes. Sand recovered from the coarse fraction of the milling operation has been used in limited backfilling. Remaining tailings have been impounded. Open-pit mining was restricted to late operations at the Blacktail pit.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Mine-drainage data: Water draining the Blackbird mine and waste rock/tailings piles is highly acidic and contains high to extreme dissolved metal concentrations (fig. 3), including thousands of mg/l copper and sulfate, hundreds of mg/l cobalt and iron, tens of mg/l aluminum, hundreds of $\mu\text{g/l}$ zinc, and tens of $\mu\text{g/l}$ arsenic (Baldwin and others, 1978; Reiser, 1986; McHugh and others, 1987). In light of the arsenic-rich cobaltite (CoAsS)-bearing ore, dissolved arsenic concentrations are less than might be expected, probably as a consequence of efficient arsenic adsorption by hydrous iron oxide minerals in stream channels with low pH. If treatment of acid mine drainage at Blackbird involves large-scale "liming" to raise pH, considerable amounts of arsenic may be desorbed and mobilized.

Natural drainage water: Geochemical data for the Special Mining Management Zone—Clear Creek is presented by McHugh and others (1987); see Lund and others, 1983 for a description of the geology of this area. Available studies of water chemistry for the Blackbird area have concentrated on streams draining mined areas and do not provide adequate background values for anthropogenically undisturbed regions. McHugh and others (1987) collected a few samples from drainages in mineralized but unmined areas; the results may indicate a very small copper-cobalt anomaly. However, sampling was conducted in July, after Spring runoff, when anomalous abundances (if present) are generally most pronounced. A study in which samples are collected throughout the annual hydrologic cycle, including geographically distributed samples from mineralized and unmineralized parts of the Yellowjacket stratigraphy, is needed to properly define natural drainage chemistry.

Potentially economically recoverable elements: High abundances of dissolved copper and cobalt are potentially recoverable by redox-reaction methods or capture by resins or zeolites (Desborough, 1994, 1995).

Metal mobility from solid mine wastes

Numerous studies indicate very high mobility of metals and acid water from solid mine waste primarily due to the ready availability of iron sulfide minerals (Baldwin and others, 1978; Reiser, 1986; McHugh and others, 1987; and sources referenced by these reports). Capillary action coupled with evaporation on waste piles during winter months

and during dry periods through the remainder of the year produce readily dissolved salts that contain metals and produce acid. Flushing during the early part of Spring runoff and also during thunderstorms causes dissolution of these salts; large metal load and acidity increases result from these flushing events (Baldwin and others, 1978; Farmer and Richardson, 1980; Reiser, 1986). High metal content (especially copper) of streams draining the Blackbird mine area have had a detrimental effect on anadromous fish populations (Reiser, 1986 and references cited therein).

Soil, sediment signatures prior to mining

A pioneering geochemical soil sample survey (Canney and others, 1953) clearly delineated areas with anomalous cobalt and copper abundances and led to discovery of the Blacktail ore zone at Blackbird. Bennett (1977) also conducted a geochemical soil sample survey at and adjacent to Blackbird. Geochemical data for stream sediment samples are given by Bennett (1977) and Evans and others (1993); these data, including streams both affected and unaffected by past mining, readily identify areas with anomalously high metal abundances, especially cobalt and copper.

Potential environmental concerns associated with mineral processing

Sulfide-mineral-rich ore in nearly carbonate-free meta-clastic rock with limited acid-buffering capacity indicates very high potential for spatially extensive acid drainage containing thousands of mg/l copper and sulfate, hundreds of mg/l cobalt and iron, tens of mg/l aluminum, hundreds of $\mu\text{g/l}$ zinc, and tens of $\mu\text{g/l}$ arsenic. Fractured host-rock facilitates interaction between oxygenated water and underground sulfide ore, thereby perpetuating acid mine drainage.

Smelter signatures

High arsenic and sulfur ore contents are a major hazard. Current laws restrict smelting to specific sites designed to mitigate arsenic hazards. Historic smelting involved simplistic nineteenth-century methods that relied on volatilization of arsenic and sulfur, thus producing severe and widespread contamination. Recent proposals for refining Blackbird-type ore have emphasized electrochemical methods; all methods are subject to stringent environmental regulation.

Climate effects on environmental signatures

Capillary action and evaporation, which lead to the formation of soluble secondary salts during the winter and dry periods, result in early spring and thunderstorm-related runoff with high metal loads and acidity. Mineralogical work is needed to detail information on the salts and their relation to the annual hydrologic cycle.

Geoenvironmental geophysics

Various electrical geophysical techniques can identify potential sources of acid mine generation and trace plumes of contaminated water away from their sources; these techniques have not been systematically applied to Blackbird deposits, however.

REFERENCES CITED

- Baldwin, J.A., Ralston, D.R., and Trexler, B.D., 1978, Water resource problems related to mining in the Blackbird mining district, Idaho: Completion Report for Supplements 35 and 48 to Cooperative Agreement 12-11-204-11, USDA Forest Service; Moscow, College of Mines, University of Idaho, 232 p.
- Bennett, E.H., 1977, Reconnaissance geology and geochemistry of the Blackbird Mountain-Panther Creek region, Lemhi County, Idaho: Idaho Bureau of Mines and Geology Pamphlet No. 167, 108 p.
- Canney, F.C., Hawkes, H.E., Richmond, G.M., and Vhay, J.S., 1953, A preliminary report of geochemical investigations in the Blackbird district: U.S. Geological Survey Open-File Report no. 221, 20 p.
- Connor, J.J., 1991, Some geochemical features of the Blackbird and Jackass zones of the Yellowjacket Formation (Middle Proterozoic) in east-central Idaho: U.S. Geological Survey Open-File Report 91-0259, 25 p.
- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- Desborough, G.A., 1994, Efficacy of heavy-metal capture by clinoptilolite-rich rocks from heavy-metal-polluted water in five drainages in Colorado: U.S. Geological Survey Open-File Report 94-140, 25 p.
- _____ 1995, Extraction of metals from raw clinoptilolite-rich rocks exposed to water in heavy-metal-polluted drainages: U.S. Geological Survey Open-File Report 95-56, 30 p.

- Earhart, R.L., 1986, Descriptive model of Blackbird Co-Cu sulfide, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 142.
- Evans, K.V., in press, The Yellowjacket Formation of east-central Idaho, *in* Berg, R.B., ed., Proceedings of Belt Symposium III: Montana Bureau of Mines and Geology Special Publication.
- Evans, K.V., Lund, K., Fairfield, R., Hopkins, R.T., Roemer, T.A., and Sutley, S.J., 1993, Analyses of rocks and stream sediment from the Special Mining Management Zone—Clear Creek, Lemhi County, Idaho: U.S. Geological Survey Open-File Report 93-708, 48 p.
- Evans, K.V., and Zartman, R.E., 1990, U-Th-Pb and Rb-Sr geochronology of Middle Proterozoic granite and augen gneiss, Salmon River Mountains, east-central Idaho: Geological Society of America Bulletin, v. 102, p. 63-73.
- Farmer, E.F., and Richardson, B.Z., 1980, Relationship of the snowpack to acid mine drainage from a western surface mine, *in* Jackson, C.L., and Schuster, M.A., eds., Proceedings: High-altitude revegetation workshop no. 4, p. 79-100.
- Lund, K., Alminas, H.V., Kleinkopf, M.D., Ehmann, W.J., and Bliss, J.D., 1990, Preliminary mineral resource assessment of the Elk City 1°x2° quadrangle, Idaho and Montana: compilation of geologic, geochemical, geophysical, and mineral deposits information: U.S. Geological Survey Open-File Report 89-0016, 118 p.
- Lund, K., Evans, K.V., and Esparza, L.E., 1983, Mineral resource potential map of the Special Mining Management Zone—Clear Creek, Lemhi County, Idaho: U.S. Geological Survey Miscellaneous Field Studies Map MF-1576-A, scale 1:50,000.
- McHugh, J.B., Tucker, R.E., and Ficklin, W.H., 1987, Analytical results for 46 water samples from a hydrogeochemical survey of the Blackbird mine area, Idaho: U.S. Geological Survey Open-File Report 87-260, 8 p.
- Modreski, P.J., and Connor, J.J., 1991, Tourmalinite and iron-formation in the Yellowjacket Formation, Idaho Cobalt Belt, Lemhi County, Idaho [abs.], *in* Good, E.E., Slack, J.F., and Kotra, R.K., eds., USGS research on mineral resources—1991 Program and Abstracts: U.S. Geological Survey Circular 1062, p. 57.
- Nash, J.T., 1989, Geology and geochemistry of synsedimentary cobaltiferous pyrite deposits, Iron Creek, Lemhi County, Idaho: U.S. Geological Survey Bulletin 1882, 33 p.
- Nash, J.T., Briggs, P., Bartel, A.J., and Brandt, E.L., 1988, Geochemical results for samples of ore and altered host rocks, Blackbird mining district, Lemhi County, Idaho: U.S. Geological Survey Open-File Report 88-661, 71 p.
- Nash, J.T., and Connor, J.J., 1993, Iron and chlorine as guides to stratiform Cu-Co-Au deposits, Idaho Cobalt Belt, USA: *Mineralium Deposita*, v. 28, p. 99-106.
- Nash, J.T., and Hahn, G.A., 1989, Stratabound Co-Cu deposits and mafic volcanoclastic rocks in the Blackbird mining district, Lemhi County, Idaho, *in* Boyle, R.W., Brown, A.C., Jefferson, C.W., Jowett, E.C., and Kirkham, R.V., eds., Sediment-hosted stratiform copper deposits: Geological Association of Canada Special Paper 36, p. 339-356.
- Plumlee, G.S., Smith, K.S., Ficklin, W.H., Briggs, P.H., and McHugh, J.B., 1993, Empirical studies of diverse mine drainages in Colorado: Implications for the prediction of mine-drainage chemistry: Proceedings, 1993 Mined Land Reclamation Symposium, Billings, Montana, v. 1, p. 176-186.
- Purdy, T.L., Milton, N.M., and Eiswerth, B.A., 1986, Spectral reflectance of vegetation in the Idaho Cobalt district-- Potential for exploration using remote sensing: U.S. Geological Survey Open-File Report 86-587, 9 p.
- Reiser, D.W., 1986, Panther Creek, Idaho, habitat rehabilitation - final report: Bonneville Power Administration Project No. 84-29, Contract No. DE-AC79-84BP17449, 479 p.
- Smith, K.S., Plumlee, G.S., and Ficklin, W.H., 1994, Predicting water contamination from metal mines and mining wastes: U.S. Geological Survey Open-File Report 94-264, 112 p.

CREEDE, COMSTOCK, AND SADO EPITHERMAL VEIN DEPOSITS (MODELS 25b,c, and d; Mosier and others, 1986a,b, and c)

by Geoffrey S. Plumlee, Kathleen S. Smith, Byron R. Berger,
Nora Foley-Ayuso, and Douglas P. Klein

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

These deposits consist of veins, stockwork veins, and mineralized breccias associated with intermediate to felsic volcanic centers in areas of regional faulting. Simple and complex sulfide minerals (those that contain arsenic, antimony, or bismuth), gold, electrum, silver, \pm telluride and selenide minerals are important ore constituents. Quartz, carbonate minerals, and adularia (\pm barite, chalcedony, and fluorite) are important gangue minerals. Mineral assemblages in many veins are characterized by well developed lateral and vertical zonation; this zonation may be present within an ore shoot, within a vein or vein system, or within entire districts. Most Creede-type veins are silver-rich, and are dominated by pyrite, sphalerite, galena, and chalcopyrite; variable amounts of carbonate minerals, quartz, and barite are present. Most Comstock-type veins are gold-rich, and are dominated by quartz and adularia \pm carbonate minerals; pyrite, sphalerite, galena, and other sulfide minerals comprise less than several percent of these veins. Sado-type veins are copper-rich equivalents of Comstock-type veins; quartz, adularia, and carbonate minerals are more abundant than chalcopyrite. Wall rock alteration assemblages, including silicic, propylitic, argillic, and advanced argillic assemblages, associated with all three epithermal vein deposit types display well developed lateral and vertical zonation. Intense silicification and pervasive argillic and advanced argillic alteration are common adjacent to shallow parts of veins, wall rock near deep parts of veins is moderately affected by silicification (\pm potassic alteration), and wall rock distal to veins contains propylitic mineral assemblages.

Examples

Creede-type: Creede, Silverton, Bonanza, Colo.; Worlds Fair, Ariz. Comstock-type: Comstock, Nev. Sado-type: Sado, Japan.

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include hot-spring Au-Ag (Model 25a); quartz alunite-epithermal (Model 25e); and, if carbonate-bearing rocks are present, polymetallic replacement (Model 19a) deposits.

Potential environmental considerations

- (1) Geoenvironmental signatures associated with different parts of epithermal vein deposits are highly variable on all scales due to well developed spatial zonation within vein and alteration mineral assemblages.
- (2) Pyrite contents of vein ore and carbonate contents of ore and wall rock principally determine the pH and metal content of water draining mines, mine waste piles, and tailings associated with epithermal vein deposits. Veins that contain abundant pyrite and base metal sulfide minerals, relative to carbonate minerals, and veins in rocks with low acid-buffering capacity, such as those affected by silicification and argillic or advanced argillic alteration, have enhanced potential for associated acidic drainage water that contains elevated abundances of dissolved iron, aluminum, manganese, zinc, copper, and lead. Water draining pyrite- and carbonate-rich ore or ore hosted by carbonate-bearing rocks tends to have near-neutral pH but elevated abundances of copper and zinc.
- (3) Historically, gold-rich ore was processed by crushing and mercury amalgamation; soil and stream sediment around historic mining and milling sites may be mercury contaminated. After the late 1800s or early 1900s, amalgamation was less common in ore processing; instead, sulfide-mineral-rich ore was roasted and gold was recovered by cyanidation. After milling, some of this ore was smelted. Soil in areas around roasting or smelting sites may be contaminated by elevated abundances of lead, zinc, copper, arsenic, or antimony.

Mitigation and remediation strategies for potential environmental concerns presented above are described in the section below entitled "Guidelines for mitigation and remediation."

Exploration geophysics

Geophysical expressions of precious-metal epithermal veins and stockworks have been reviewed by Allis (1990), Irvine and Smith (1990), Klein and Bankey (1992), and Watson and Knepper (1994). Silicic and carbonate alteration of volcanic rocks produces reflectance and thermal infrared contrasts and increases their resistivity and density; the extent of associated anomalies can be delineated with detailed gravity, multispectral remote sensing (Arribas and

others, 1989; Collins, 1989), and direct current and electromagnetic (Nishikawa, 1992) surveys, respectively. Gravity anomalies may be complicated by open fractures and brecciated rock, which reduce bulk density. Electrical and gravity anomalies associated with epithermal deposits may be difficult to distinguish from those caused by small intrusions or faults. Resistivity lows and reflectance contrasts associated with argillically altered rock can be delineated by electrical mapping (Bisdorf, 1995) and multispectral remote sensing, respectively. The distribution of clay zones and electrical chargeability associated with sulfide minerals can be mapped with induced polarization. Airborne photography and side-looking radar can identify topographic features that may be related to resistant silicic and carbonate zones and easily-weathered areas affected by argillic alteration. Areas that contain altered magnetite can be outlined by magnetic surveys. Rock affected by potassic alteration can be identified by spectral gamma-ray surveys. Regional gravity, aeromagnetic, and satellite or airborne remote sensing images may help identify linear, circular, and intersecting features associated with calderas and faulted volcanic terranes in which additional detailed surveys are warranted.

References

Geology: Becker (1882), Steven and Ratté (1965), Buchanan (1981), Berger and Eimon (1983), Hayba and others (1985), Heald and others (1987).

Environmental geology and geochemistry: Moran (1974), Plumlee and others (1993), Smith and others (1994).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

The size of most deposits is small (10,000 tonnes) to moderate (several million tonnes). However, a few districts are large to extremely large, including Casapalca, Peru, and Comstock, Nev. (10-20 million tonnes), and Pachuca-Real del Monte (Mexico) (>100 million tonnes).

Host rocks

Epithermal vein deposits are in intermediate to felsic volcanic rocks (andesite, dacite, quartz-latitude, rhyodacite, and rhyolite) and associated volcanoclastic and sedimentary rocks (for example, those deposited in volcanic depressions such as caldera moats).

Surrounding geologic terrane

Most epithermal vein deposits are areas of regional faulting within intermediate to felsic volcanic fields, including volcanoes and caldera complexes from which volcanic rocks that host the deposits were erupted.

Wall-rock alteration

Wall rock alteration assemblages are characterized by strong vertical and lateral zonation between deep, central parts of veins and shallow and (or) distal parts of veins (fig. 1). In many (but not all) districts, host volcanic rocks are altered to propylitic assemblages, including chlorite, epidote, calcite, and pyrite, on a regional or district-wide basis; this type of alteration is distal to most veins. In the central parts of districts alteration varies as a function of depth. At deep levels, the alteration assemblage is characterized by quartz and chlorite \pm some potassic alteration (adularia). At intermediate levels the alteration assemblage consists of quartz; sericite; and illite, which may grade upward and distally to lower-temperature smectite; \pm zeolite minerals. At shallow levels, alteration is characterized by massive silicification, formation of chalcedonic sinter, and pervasive acid-sulfate alteration, including alteration to kaolinite and alunite. In laterally distal parts of districts, rock adjacent to veins may be locally silicified and (or) pyritized. In some places, wall rock along upper parts of veins may be altered to illite, smectite, and alunite or kaolinite.

Nature of ore

Veins and stockwork veins fill fractures in intermediate to felsic volcanic rocks. Veins vary greatly in width, from less than several cm to more than 3 m. Most veins display banded layers characterized by substantial mineralogic differences; the veins can also be quite vuggy and include considerable open space.

Deposit trace element geochemistry

The geochemistry of epithermal veins varies laterally and vertically. Altered wall rock adjacent to veins can have significant enrichments in mineralization-related trace elements (Foley and Ayuso, 1993).

Creede-type: Specific parts of these veins are characterized by elevated abundances of various elemental suites as follows: Deep parts of central veins- Au, Cu, Pb, Zn, \pm Ag, \pm Te, \pm Se. Intermediate parts of central veins- Pb, Zn,

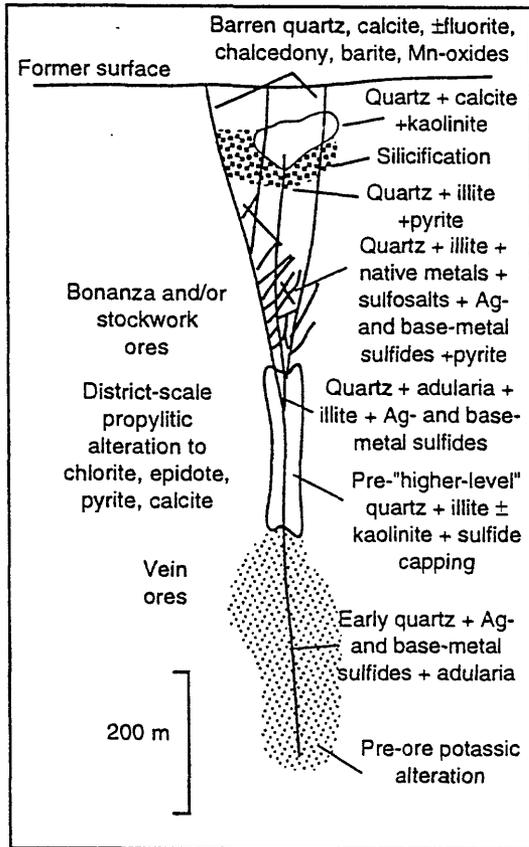


Figure 1. Schematic cross section through an epithermal vein deposit showing distribution of vein and wall rock alteration minerals. Modeled primarily after Creede-type veins; however, with the exception that base metal sulfide minerals are less abundant, the same general zoning patterns are present in Comstock-type vein ore. Figure modified from Mosier and others (1986a) and Berger and Eimon (1983).

Ag, Cu, \pm Mn. Intermediate to shallow parts of central and distal veins- As, Sb, Hg, \pm Au, \pm Mn, \pm Se. Distal, deep parts of veins- Ag, Pb, Zn, \pm Cu, \pm Ba, \pm As, \pm Sb, \pm Mn, \pm Se.

Sado and Comstock-type: Geochemical zonation within most Comstock-type veins is similar to that in Creede-type veins, except that lead and zinc are less abundant throughout all parts of veins.

Ore and gangue mineralogy and zonation

Minerals are listed in approximate decreasing order of abundance. Potentially acid-generating minerals are underlined; those that are acid-generating when oxidized by aqueous ferric iron are denoted by *.

Creede-type veins are base-metal sulfide mineral rich. They contain abundant sphalerite*, galena*, chalcopryrite, and pyrite; lesser amounts of many other sulfide and sulfosalt minerals, such as argentite*, tetrahedrite, pyrargyrite, \pm marcasite, \pm botryoidal pyrite; and variable but generally subordinate amounts of quartz, carbonate minerals (including rhodochrosite, calcite, Mn-siderite), adularia, fluorite, manganese silicate minerals (such as pyroxmangite), barite, and chalcedony.

Comstock- and Sado-type veins are dominated by quartz and adularia and contain variable amounts of carbonate minerals and generally subordinate amounts of sulfide minerals, including pyrite, sphalerite*, galena*, chalcopryrite, and arsenopyrite.

All three vein types tend to be enriched in manganese; abundances of rhodochrosite or manganiferous calcite are moderate to high, and manganese silicate minerals are also abundant. Well developed lateral and vertical vein mineralogy zonation is typical within ore shoots, within veins, and across districts (figs. 1 and 2). This zonation results from variations in the hydrologic and geochemical processes that prevailed during hydrothermal ore genesis.

Mineral characteristics

Textures: Mineral grains can vary from fine to coarse (<1 mm to >10 cm), depending upon the particular district

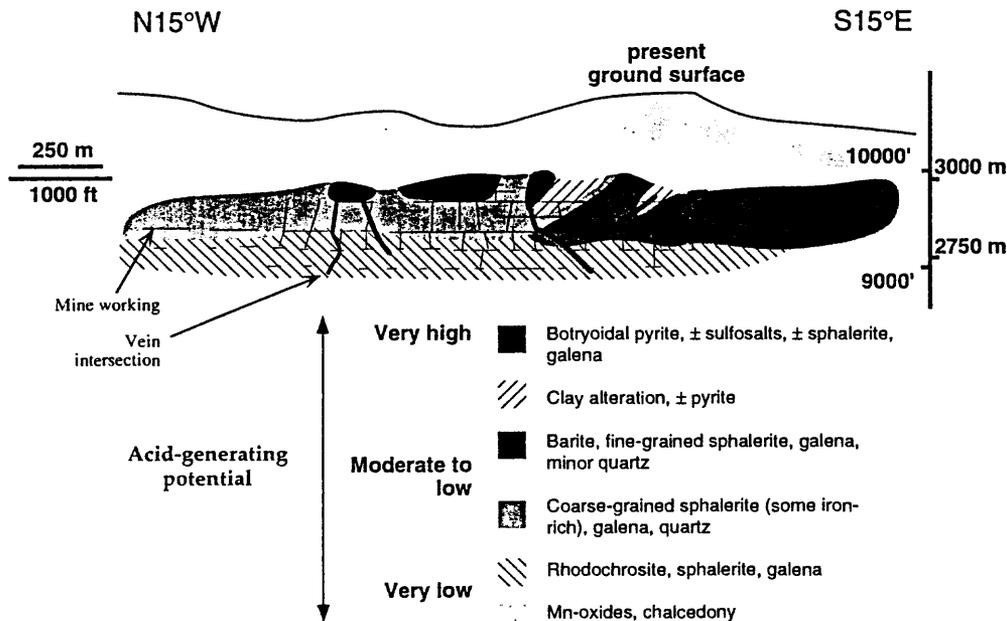


Figure 2. Longitudinal section of the A vein, Bulldog Mountain vein system, Creede district, Colorado, showing lateral and vertical vein mineral zoning patterns. The various mineralogic zones are ranked according to their potential to generate acid drainage water from mine workings or mine waste. A poorly-welded ash-flow tuff occurs immediately above the botryoidal pyrite zone. Fracture permeability in this ash flow tuff is very low, and so the botryoidal pyrite has largely escaped oxidation even though it occurs well above the present water table, which is within the deep rhodochrosite-dominant zone. Ground water that does penetrate beneath the ash flow tuff becomes highly acid, but evaporates, while still in the mine workings, and leaves behind melanterite and goslarite efflorescent salts. Figure modified from Plumlee and Whitehouse-Veaux (1994).

and location within the district. Textures range from euhedral to botryoidal to massive. Crustification sequences are often well developed; bands comprised of one mineral assemblage may be overgrown by one or more successive, mineralogically distinct bands.

Trace element contents: Sphalerite can have low to high iron contents (<1 to >15 mol percent), several tenths to 1 mol percent cadmium, and minor amounts of other trace elements, including silver. Galena can contain silver; <1 mol percent in most cases. Botryoidal pyrite and marcasite can have very high concentrations (as much as 15 weight percent, combined) of arsenic, antimony, silver, mercury, tellurium, selenium, and (or) gold. Carbonate minerals commonly form extensive solid solutions that include manganiferous calcite, kutnahorite, and siderite.

General weathering rates: Euhedral to massive, coarse-grained, interlocking sulfide minerals weather at very slow rates; samples of these crystals exposed on mine dumps in cool wet climates for >100 years can still appear fresh and unweathered. Most botryoidal pyrite and marcasite, especially if enriched in arsenic, antimony, and other trace elements, weather very rapidly, in some cases simply by atmospheric water vapor sorption. Rates at which carbonate minerals weather are variable, but increase with decreasing grain size and increasing trace element content. For example, iron-rich calcite and rhodochrosite weather more readily than equivalent minerals with low iron contents. Weathering rates for minerals can be quite high in warm, humid climates.

Secondary mineralogy

Readily soluble minerals underlined. Minerals formed by weathering prior to mining include goethite, jarosite, alunite, halloysite, anglesite, cerussite, smithsonite, manganese-oxide minerals (psilomelane, pyrolusite, braunite), and cerargyrite. Minerals formed by weathering subsequent to mining are primarily soluble sulfate minerals indicative of deposition from locally highly acidic water. Zinc sulfate minerals include goslarite. Iron sulfate minerals noted in published reports include melanterite, although other sulfate minerals, such as copiapite, are also probably present in pyrite-rich ore. Hydrous ferric oxide and iron hydroxysulfate minerals, such as ferrihydrite and schwertmanite, precipitate from acidic to near-neutral mine- and natural- drainage water. Aluminum hydroxysulfate minerals, including basaluminite and jurbanite, precipitate from water having pH between 4.5 and 5.

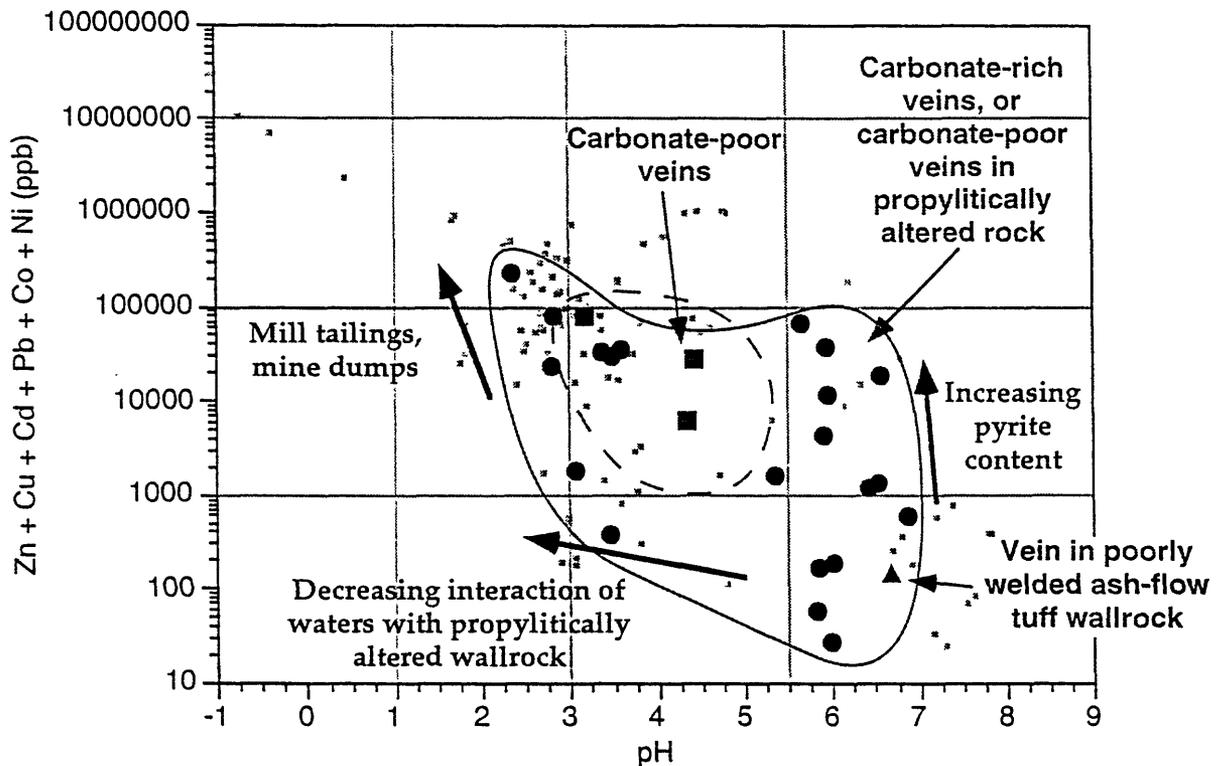


Figure 3. Ficklin plot showing variations in pH and sum of dissolved base metals Zn, Cu, Cd, Co, Ni, and Pb in mine and natural water draining epithermal veins of various geologic characteristics.

Topography, physiography

Silicified zones and quartz-chalcedony veins tend to form topographic highs. Clay altered zones probably erode more rapidly than adjacent less altered rocks, and form topographic lows.

Hydrology

Mine workings provide the most permeability for ground water flow. Faults, joints, and veins, which also focus ground water flow, provide the greatest natural permeability. Flow along unmineralized fractures and vuggy, open-space veins with continuous permeability is greatest; flow along veins completely filled by ore and gangue is minimal. Fracture permeability is also commonly reduced where fractures cross poorly welded ash flow tuffs, and in zones of intense clay alteration; these rocks and altered zones are aquitards or barriers to ground water flow. For example, epithermal ore at Creede is capped by poorly welded tuff that inhibited ascending hydrothermal fluids that formed the deposit and presently inhibits descending oxidized ground water. Most of a zone of botryoidal pyrite that formed directly beneath the cap rock is unoxidized even though it occurs well above the present-day water table; as a result, acid drainage from the botryoidal pyrite zone is very limited, and evaporates prior to exiting mine workings developed in the zone. Zones of hydrothermal brecciation can also be ground water conduits, provided sufficient open space remains; if no open space is present, these breccia zones may impede ground water flow.

Mining and milling methods

Historic: Most epithermal veins were mined in underground tunnels and stopes. However, open pits and glory holes developed in some districts. Mineral processing typically involved milling, gravity separation of coarse precious metals, mercury amalgamation to extract gold and silver, and flotation to extract lead, zinc, and copper. Sulfide concentrates were smelted in some historic districts.

Modern: Due to the potential for ore dilution by wall rock, vein ore is still largely extracted by underground mining. Deposits in which economic ore is disseminated through large volumes of near-surface rock, such as shallow stockwork vein systems or mineralized sedimentary rocks exposed in caldera moats, can be mined using open pit

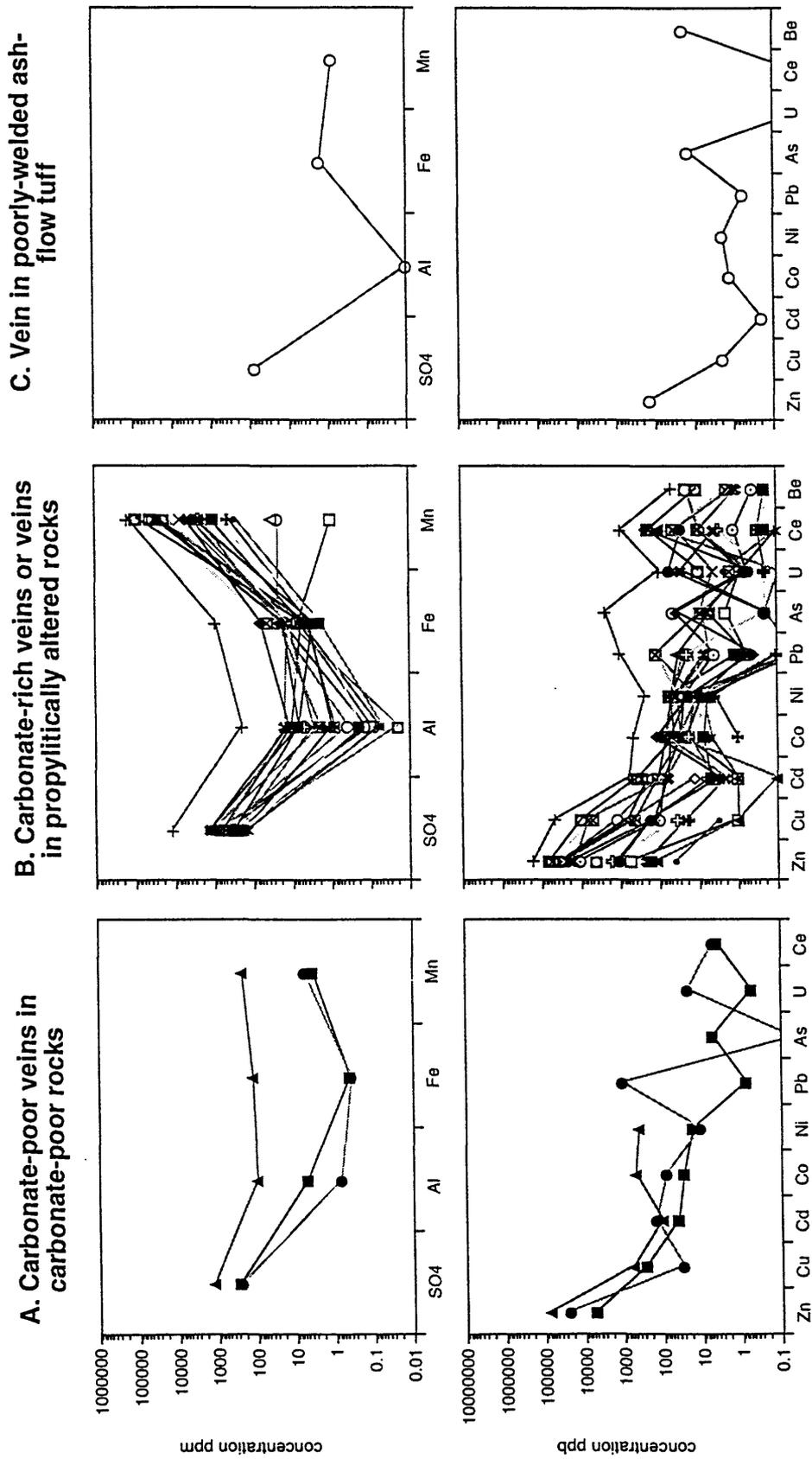


Figure 4. Plots showing concentrations of dissolved constituents in water draining epithermal veins of various geologic characteristics.

techniques. After the late 1800s to early 1900s, processing by amalgamation was increasingly replaced by cyanidation; most sulfide-mineral-rich ore has been roasted prior to cyanidation. Advances in mineral processing technology have recently led to a decline in roasting, however. Most modern processing involves milling, which is followed by cyanidation and extraction of precious metals via carbon-in-pulp or electrowinning. Stopes are backfilled with coarse tailings materials and fine tailings are stored in surface impoundments.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Mine-drainage data: Mine drainage data (figs. 3 and 4) pertinent to the Creede, Silverton, and Bonanza, Colo., and Worlds Fair, Ariz., deposits are summarized from Moran (1974), Plumlee and others (1993), Smith and others (1994), and Plumlee and others (in press).

Mine water that drains underground workings in deposits that contain sphalerite, galena, and pyrite in ore with low carbonate mineral contents tends to be acidic, pH ranges from 3 to 5, and contain elevated dissolved metal abundances, including hundreds of mg/l iron, aluminum, and manganese; several to several tens of mg/l zinc and copper; and as much as 1 mg/l lead. Water draining arsenic- and pyrite-rich ore can potentially contain several hundreds of $\mu\text{g/l}$ to several mg/l dissolved arsenic.

Water that drains pyrite-rich tailings and waste dumps can be quite acidic and contain elevated dissolved metal abundances, including thousands of mg/l iron, aluminum, and manganese; tens to hundreds of mg/l zinc and copper; and hundreds of $\mu\text{g/l}$ to several mg/l lead, cadmium, arsenic, and other metals.

Mine water that drains underground workings in carbonate-rich ore, or ore in which water reacts with propylitically altered rock, tends to be near-neutral, pH values range from 5.5 to 7, and contain as much as tens of mg/l dissolved zinc and several mg/l dissolved copper, if ore is pyrite rich.

Mine water that drains underground workings in pyrite-rich veins hosted by propylitically altered rocks can be highly acidic and contain high dissolved metal contents if water flows along veins and does not react with wall rock carbonate minerals. As an example, in 1973, water in the Rawley drainage tunnel, which drains pyrite-sphalerite-galena veins in the Bonanza district, Colo., had a pH near 3.2 and contained high dissolved metal abundances (Moran, 1974). Subsequently, the adit collapsed, which eliminated interaction between ore and atmospheric oxygen and increased interaction between water and carbonate minerals in propylitically altered wall rock. Consequently, the water now has pH values near 6 (Plumlee and others, 1993; Smith and others, 1994) and contains significantly lower dissolved iron and aluminum contents; zinc and copper abundances are essentially unchanged.

Mine water that drains a vein hosted by poorly-welded ash-flow tuff (Creede, Colo.) has a near-neutral pH of 6.7 and contains low dissolved metal contents (Plumlee and others, 1993). The near-neutral pH may result from interaction between water and fine-grained, devitrified glass in poorly welded tuff. Low metals contents may reflect a lack of base metal sulfide minerals in the veins.

Manganese enrichments characteristic of epithermal vein ore cause mine drainage water to have elevated manganese abundances relative to those of iron and aluminum.

Natural-drainage data: Water draining broad areas of propylitically altered rocks can have near-neutral pH and relatively low dissolved abundances of aluminum, lead, arsenic, and copper. This water may have slightly elevated dissolved abundances of some metals, including as much as several mg/l zinc, iron, and manganese. Water draining sulfide-bearing fractures has significantly lower pH and contains correspondingly higher dissolved metal abundances.

Metal mobility from solid mine wastes

Metals and acid are readily liberated from pyrite-rich mine waste and intermittently wet/dry mine workings due to the rapid dissolution of soluble secondary salts. Secondary salt dissolution (and resulting acid and metal generation) is much more rapid than acid consumption by carbonate minerals in dumps or surrounding mine workings. The soluble salts form coatings on mine waste, and fracture fillings in rocks and coatings on mine workings above the water table.

Storm water samples: No data available. However, vegetation kill zones downhill from pyrite-rich mine dumps indicate that highly acidic, metal-rich water can be generated, particularly by secondary salt dissolution, in spite of abundant carbonate-rich rocks on mine dumps.

Soil, sediment signatures prior to mining

Elevated abundances of some metals, including Pb, Mn, Fe, \pm Zn, Cu, As, Sb, Hg?, are probably present downslope from vein outcroppings due to mechanical erosion of oxidized vein ore. Elevated abundances of elements

concentrated in oxidized vein ore, including Pb, Mn, Fe, \pm Zn, Cu, As, Sb, Hg?, are probably dispersed into nearby stream sediments.

Potential environmental signatures associated with mineral processing:

Historically, gold-rich ore was processed using crushing and mercury amalgamation. Consequently, soil around historic mining and milling sites may be contaminated with mercury. After the late 1800s or early 1900s, processing by amalgamation became less common; sulfide-rich ore was roasted and treated by cyanidation. Roaster particulates may potentially have contaminated soil and sediment in areas surrounding roasting sites with various metals, including lead, zinc, copper, arsenic, antimony, tellurium, and selenium.

Smelter signatures

Sulfide-rich ore was smelted in a number of historic districts. In districts with identified historic smelting activity, soil may contain locally elevated abundances of lead, zinc, copper, \pm arsenic, \pm antimony, \pm selenium, \pm tellurium.

Climate effects on environmental signatures

Currently available data mostly pertain to moderately wet, seasonally temperate climatic regimes of the Rocky Mountains; limited data are available for the Worlds Fair, Ariz., district in a relatively hot, dry climate. Mine drainage in the Worlds Fair district has significantly lower pH and higher metal contents than water draining geologically similar veins in a cooler climate at Creede, Colo. Lower pH and higher metal contents may reflect increased evaporation within mine workings, and periodic formation and flushing of soluble salts; however, more data are needed to verify this speculation. No data are available on effects relating to evaporation of near-neutral pH water draining carbonate-rich ore; evaporation of iron-poor water probably causes pH to increase. Mobilization of arsenic, uranium, and possibly selenium (if present in ore) may be enhanced in dry climates if drainage water is alkaline. Climate can strongly affect mineral weathering rates; rates are greatest in warm, humid climates.

Potential environmental effects:

Acid drainage from pyrite- and sulfide-rich veins may adversely affect ground water quality in either wet or dry climates.

- (1) The greatest potential for deleterious downstream environmental effects pertain to deposits that consist of pyrite-, sphalerite-, galena-, (\pm chalcopyrite)-rich ore in carbonate-mineral poor veins; deposits in volcanic terranes minimally affected by propylitic alteration, in which associated water has low acid-buffering capacity; and deposits in which historic mining operations released significant volumes of fine-grained pyritic tailings, which have become part of the sediment column, into rivers or streams. Oxidation of associated tailings can facilitate long-term metal and acid releases, which result in water quality degradation. Downstream effects of acid drainage can be potentially extensive; copper, zinc, manganese, and lesser cadmium can remain mobile for significant distances downstream.
- (2) Less significant downstream effects are most likely to be associated with deposits that principally consist of carbonate-bearing vein ore; veins in propylitically altered rock, which tend to have drainage water with near-neutral pH values; and deposits in dry climates, where water evaporates or seeps underground. Zinc and manganese are the principal elements that remain mobile, either in solution or as colloids (Kimball and others, 1995), for the greatest distances downstream. Some arsenic, uranium, selenium, and molybdenum may be mobilized if drainage water is alkaline.
- (3) Zones that contain abundant botryoidal pyrite or marcasite have especially high acid drainage generation potential.
- (4) Acidic, metal-rich water can develop in pyrite-rich tailings or waste dumps, even if carbonate minerals are present because secondary salt dissolution, and resulting acid and metal generation, is much more rapid than acid consumption by carbonate minerals.
- (5) Arsenic and antimony, to a lesser extent, may pose health risks in water draining ore that contains abundant sulfosalt or sulfide minerals that contain elevated abundances of arsenic and antimony; arsenic and antimony abundances are greatest in acid water, but can be moderately high in near-neutral water.

Guidelines for mitigation and remediation:

Careful documentation of district- and mine-scale mineral zoning patterns; rock, soil, and water chemistry; and structural features is important to understand potential variability of environmental signatures.

- (1) Acid water can be remediated successfully using lime addition and sodium-bisulfide precipitation of metals; a potentially acid-generating sludge is created. If drainage water is relatively iron-poor, such as most water having near-neutral pH, the amount of particulates formed by liming may be insufficient to effectively sorb all zinc,

cadmium, and nickel. Lime addition to iron-rich drainage water may generate sufficient suspended particulates onto which a major fraction of dissolved arsenic, lead, and copper can sorb, thereby reducing or eliminating need for sodium bisulfide addition; the resulting particulate sludge is non-acid-generating as well. If ore is arsenic-, selenium- or uranium-rich, liming to excessively high pH values may enhance mobility of these elements.

(2) The utility of carbonate-bearing, propylitically altered host rocks in acid drainage mitigation should be considered. For example, acid water could be channeled, away from veins, through these rocks via artificial or natural fractures to help reduce acidity.

(3) Constructed wetlands may be useful in mitigation of less acidic mine water.

(4) Careful mapping of fractures, which focus ground water flow, and poorly welded ash flow tuffs and clay alteration zones, which restrict ground water flow, is essential for an adequate understanding of site hydrology.

(5) Isolation of pyrite-rich waste from weathering and formation of soluble secondary salts is crucial in eliminating storm- and snowmelt-related pulses of acid and metals into surface water. High carbonate mineral content in dump material is not sufficient to prevent acid pulses because soluble secondary salts generate acid and metals much faster than carbonate minerals can consume acid.

(6) In modern milling operations, pyritic parts of mill tailings should be used as underground backfill to prevent accidental release of acid-generating material into downstream sediments.

Geoenvironmental geophysics

Geophysical applications to geoenvironmental investigations are reviewed by King and Pesowski (1993), Watson and Knepper (1994), and Paterson (1995). An example high-resolution airborne multispectral imagery applied to a geoenvironmental investigation is given by King (1995). Highly acidic and (or) metal-enriched ground water is highly conductive and may produce vegetation stress; associated anomalies can be identified by electrical and multispectral imaging methods, respectively. Surface water that contains suspended materials or has high conductivity can also be identified on multispectral imagery. Electrically conductive clay aquitards formed during mineralization or by weathering of ash-flow tuff can be delineated using electromagnetic and induced polarization/resistivity techniques. Distributions of electrically chargeable sulfide minerals can be mapped with induced polarization. Shallow mine workings may be located by electrical, seismic refraction, and gravity surveys, and may be identifiable on infrared thermal imagery. Low-resistivity fluids, whose flow is channeled by brecciated rock, faults, and joints, can be identified by gravity and electrical surveys.

REFERENCES CITED

- Allis, R.G., 1990, Geophysical anomalies over epithermal systems: *Journal of Geochemical Exploration*, v. 36, p. 339-374.
- Arribas, Antonio, Jr., Rytuba, J.J., Rye, R.O., Cunningham, C.G., Podwysocki, M.H., Kelly, W.C., Arribas, Antonio, Sr., McKee, E.H., and Smith, J.G., 1989, Preliminary study of the ore deposits and hydrothermal alteration in the Rodalquilar caldera complex, southeastern Spain: U.S. Geological Survey Open-file Report 89-327, 39 p.
- Becker, G.F., 1882, *Geology of the Comstock Lode and the Washoe district*: U.S. Geological Survey Monograph 3, 422 p.
- Berger, B.R., and Eimon, P.I., 1983, Conceptual models of epithermal metal deposits in Shanks, W.C., ed., *Cameron Volume on Unconventional Mineral Deposits*: Society of Mining Engineers, New York, p. 191-205.
- Bisdorf, R.J., 1995, Correlation of electrical geophysical data with lithology and degree of alteration at the Summitville mine site, in *Summitville Forum '95*: Colorado Geological Survey, Special Publication 38, p. 70-63.
- Buchanan, L.J., 1981, Precious metal deposits associated with volcanic environments in the southwest, in Dickinson, W.R., and Payne, W.D., eds., *Relations of Tectonics to Ore Deposits in the Southern Cordillera*: Arizona Geological Society Digest, v. XIV, p. 237-261.
- Collins, A.H., 1989, Thermal-infrared spectra of altered volcanic rocks in the Virginia Range, Nevada: *Proceedings of the 7th Thematic Conference on Remote Sensing for Exploration Geologists*, October 2-6, 1989, Calgary, Alberta, Canada, Environmental Research Institute of Michigan, Ann Arbor, Michigan, p. 1335-1340.
- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- Foley, N.K., and Ayuso, R.A., 1993, Trace element and Pb isotopic geochemistry of Au-Ag vein assemblages and volcanic wall rock, North Amethyst, Creede district, CO [Abs]: *Abstracts with Programs, Geological Society of America*, v. 25, p. A-164.

- Hayba, D.O., Bethke, P.M., Heald, P., and Foley, N.K., 1985, Geologic, mineralogic, and geochemical characteristics of volcanic-hosted epithermal precious metal deposits, *in* Berger, B.R., and Bethke, P.M., eds., *Geology and Geochemistry of Epithermal Systems: Society of Economic Geologists Reviews in Economic Geology*, v. 2, p. 129-168.
- Heald, P., Foley, N.K., and Hayba, D.O., 1987, Comparative anatomy of volcanic-hosted epithermal deposits; acid-sulfate and adularia-sericite types: *Economic Geology*, v. 82, p. 1-26.
- Irvine, R.J. and Smith, M.J., 1990, Geophysical exploration for epithermal gold deposits: *Journal of Geochemical Exploration*, v. 36, no. 1/3, p. 375-412.
- Kimball, B.A., Callender, E., and Axtmann, E.A., 1995, Effects of colloids on metal transport in a river receiving acid mine drainage, upper Arkansas River, Colorado, USA: *Applied Geochemistry*, v. 10, p. 285-306.
- King, T.V.V., 1995, Environmental considerations of active and abandoned mine lands: *U.S. Geological Survey Bulletin* 2220, 38 p.
- King, A. and Pesowski, M., 1993, Environmental applications of surface airborne geophysics in mining: *Bulletin of the Canadian Institute of Mining and Metallurgy Bulletin*, v. 86, no. 966, p. 58-67.
- Klein, D.P., Bankey, V.L., 1992, Composite geophysical model for continental volcanic-hosted epithermal mineralization: Cox and Singer mineral deposit models numbered 25b, 25c, 25d, and 25e: *U.S. Geological Survey Open-file Report* 92-389, 15 p.
- Moran, R.E., 1974, Trace element content of a stream affected by metal-mine drainage, Bonanza, Colorado: Austin, University of Texas, Ph.D. thesis, 167 p.
- Mosier, D.L., Berger, B.R., and Singer, D.A., 1986c, Descriptive model of Sado epithermal veins, *in* Cox, D.P., and Singer, D.A., eds., *Mineral Deposit Models: U.S. Geological Survey Bulletin* 1693, p. 154.
- Mosier, D.L., Sato, T., Page, N.J., Singer, D.A., and Berger, B.R., 1986a, Descriptive model of Creede epithermal veins, *in* Cox, D.P., and Singer, D.A., eds., *Mineral Deposit Models: U.S. Geological Survey Bulletin* 1693, p. 145-146.
- Mosier, D.L., Singer, D.A., and Berger, B.R., 1986b, Descriptive model of Comstock epithermal veins, *in* Cox, D.P., and Singer, D.A., eds., *Mineral Deposit Models: U.S. Geological Survey Bulletin* 1693, p. 150.
- Nishikawa, Nobuyasu, 1992, The use of electrical methods in recent exploration for epithermal gold deposits in Japan: *Exploration Geophysics*, v. 23, no.1 and 2, p. 249-254.
- Paterson, Norman, 1995, Application of geophysical methods to the detection and monitoring of acid mine drainage: *in* Bell, R.S., *Proceedings of the symposium on the application of geophysics to engineering and environmental problems: Orlando, Florida, April 23-26, 1995*, Environmental and Engineering Geophysical Society, p. 181-189.
- Plumlee, G.S., Smith, K.S., Ficklin, W.H., Briggs, P.H., and McHugh, J.B., 1993, Empirical studies of diverse mine drainages in Colorado: implications for the prediction of mine-drainage chemistry: *Proceedings, 1993 Mined Land Reclamation Symposium, Billings, Montana*, v. 1, p. 176-186.
- Plumlee, G.S., Smith, K.S., Montour, M., Mosier, E.L., Ficklin, W.H., *in press*, Geology-based models for the prediction of mine drainage composition: *Society of Economic Geology Reviews in Economic Geology*, v. 6B.
- Plumlee, G.S., and Whitehouse-Veaux, P.H., 1994, Mineralogy, paragenesis, and mineral zoning along the Bulldog Mountain vein system, Creede District, Colorado: *Economic Geology, Special Issue on Volcanic Centers as Exploration Targets*, v. 89, no. 8, p. 1883-1905.
- Smith, K.S., Plumlee, G.S., and Ficklin, W.H., 1994, Predicting water contamination from metal mines and mining waste: Notes, Workshop #2, International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage: *U.S. Geological Survey Open-file Report* 94-264, 112 p.
- Steven, T.A., and Ratte, J.C., 1965, Geology and structural control of ore deposition in the Creede district, San Juan Mountains, Colorado: *U.S. Geological Survey Professional Paper* 487, 90 p.
- Watson, Ken and Knepper, D.H., eds., 1994, Airborne remote sensing for geology and the environment - present and future: *U.S. Geological Survey Bulletin* 1926, 43 p.
- White, N.C., and Hedenquist, J.W., 1995, Epithermal gold deposits: styles, characteristics, and exploration: *Society of Economic Geologists Newsletter*, October, 1995, n. 23.

EPITHERMAL QUARTZ-ALUNITE AU DEPOSITS (MODEL 25e; Berger, 1986)

by Geoffrey S. Plumlee, Kathleen S. Smith, John E. Gray, and Donald B. Hoover

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Central advanced argillic zone has iron-, copper-, and arsenic-rich sulfide and sulfosalt minerals with high acid-generating capacity; deposits consist of vuggy veins and breccias in highly acid-altered volcanic rocks with very low acid-consuming capacity. Central advanced-argillic zone is flanked by argillic and distal propylitic zones with some acid-buffering capacity, decreased copper and arsenic abundances, and increased zinc and lead abundances.

Examples

Summitville and Red Mountain Pass, Colo.; Goldfield, Nev.; Paradise Peak, Nev.; Julcani, Peru.

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include porphyry copper (Model 17), porphyry gold-copper (Model 20c), and porphyry copper-molybdenum (Model 21a).

Potential environmental considerations

- (1) Dominant mining activity is in sulfide-mineral-rich, strongly altered volcanic rocks with negligible acid-buffering capacity.
- (2) Very high potential for the generation of acid-mine drainage (pH 1.5 to 3) that contains thousands of mg/l iron and aluminum; hundreds of mg/l copper and zinc (copper>zinc); hundreds of $\mu\text{g/l}$ to tens of mg/l As, Co, Ni, Cr, U, Th, rare earth elements; tens to hundreds of $\mu\text{g/l}$ beryllium; and anomalous abundances of bismuth, antimony, thallium, selenium, and (or) tellurium (Plumlee and others 1995a).
- (3) Unoxidized sulfide minerals can persist in clay-rich alteration zones to within 10 m of ground surface. Exposure of these sulfide minerals during mining can further enhance potential for acid-drainage generation.
- (4) In temperate or seasonally wet climates, soluble secondary iron, aluminum, and copper sulfate minerals dissolve during storm events and snowmelt, and lead to short term pulses of highly acidic, metal-bearing water from mine sites. The sulfate salts form by evaporation of acid mine water above the water table in open pits and underground mine workings during dry periods, even in wet climates.
- (5) Potential downstream environmental effects of acid drainage can be significant in magnitude and spatial extent, especially if surrounding terrane is composed primarily of volcanic rocks with low acid-buffering capacity. Dominant downstream signatures include water having low pH, and high iron, aluminum, manganese, copper, and zinc abundances.
- (6) Amalgamation-extraction of gold carried out during historic operations may be a residual source of mercury.
- (7) Smelter emissions at historic sites have elevated abundances of arsenic, copper, and zinc, and possibly other elements such as beryllium and tellurium.
- (8) Highly oxidized deposits and (or) deposits located in arid climates probably have lower potential for acid mine drainage and other environmental problems.
- (9) Cyanide heap leach solutions are composed predominantly of copper-cyanide complexes and thiocyanate.

Mitigation and remediation strategies for potential environmental concerns presented above are described in the section below entitled "Guidelines for mitigation and remediation."

Exploration geophysics

Resistivity studies can be used to help map features such as alteration zones. Potassium contained in alteration alunite may be identified by gamma ray spectrometry. Alteration mineral assemblages and stressed vegetation can also be identified using multispectral scanning remote sensing techniques such as AVIRIS.

References

Geology: Stoffregen (1987), Vikre (1989), Ashley (1990), John and others (1991), Deen and others (1994), and Gray and Coolbaugh (1994).
Environmental geology, geochemistry: Koyanagi and Panteleyev (1993), Gray and others (1994), Smith and others (1994), and Plumlee and others (1995a,b).

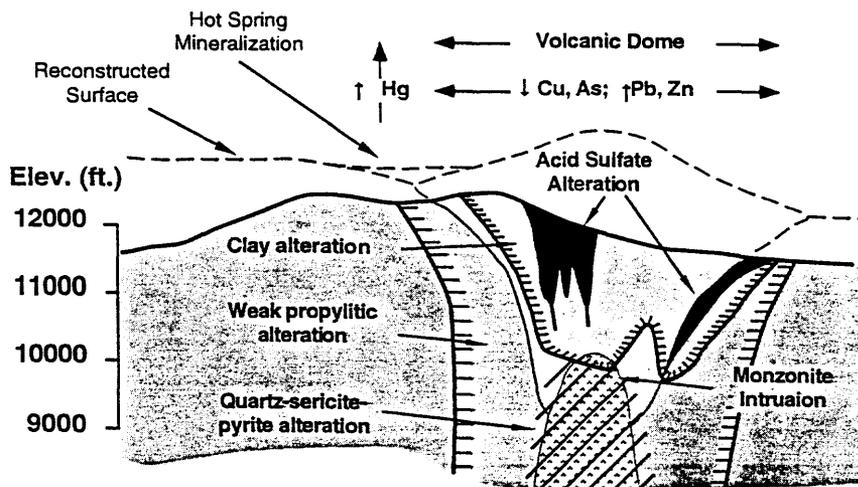


Figure 1. Simplified geologic cross section of an epithermal quartz-alunite Au deposit. Based on Summitville (Perkins and Neiman, 1982; Plumlee and others, 1995a) but modified to incorporate data from Julcani, Peru (Deen and others, 1994) and Paradise Peak, Nev., (John and others, 1991).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Deposit size is generally small (0.1 million tonnes) to intermediate (12 million tonnes).

Host rocks

These deposits are hosted by felsic volcanic rocks, generally intrusions or lava domes (fig. 1), that have low acid-buffering capacity. Most of these volcanic rocks are part of composite stratovolcano complexes. Some ore may be hosted in older sedimentary or crystalline rocks surrounding lava domes.

Surrounding geologic terrane

Surrounding geologic terrane is primarily volcanic but includes underlying sedimentary or crystalline rocks.

Wall-rock alteration

Wall-rock alteration reflects progressive wall-rock neutralization of highly acidic magmatic gas condensates; alteration predates ore formation. Alteration zoning shown on figures 1 and 2.

Intermediate-level advanced-argillic zone: Innermost vuggy silica, grading outward into quartz-alunite (\pm pyrophyllite), quartz-kaolinite, and montmorillonite-illite-smectite alteration zones. Pyrite present in all zones. Phosphate minerals present primarily (?) in quartz-alunite zone.

Intermediate-level argillic zone: Montmorillonite-smectite-illite-clay minerals with pyrite.

Peripheral propylitic zone: Alteration of volcanic rocks to chlorite \pm epidote \pm pyrite \pm calcite.

Deep phyllic zone: Quartz-sericite-pyrite.

Nature of ore

In some deposits (e.g. Summitville) disseminated sulfide minerals are focused primarily in vuggy silica, quartz-alunite, and quartz-kaolinite zones; however, significant pyrite and other sulfide minerals also are present in clay altered zones, as disseminations within breccia, and in altered wall-rock veinlets. See figure 2 for typical sulfide mineral-sulfur content ranges for Summitville alteration zones. Although sulfide mineral-sulfur content is relatively low (<5 percent), the alteration process effectively removes nearly all of the rock's capacity to buffer acid.

Deposit trace element geochemistry

Deep: copper, \pm arsenic, \pm tungsten.

Intermediate inner: copper, arsenic, gold, \pm tellurium.

Intermediate peripheral: copper, lead, zinc.

Shallow, near surface: Mercury, arsenic, antimony, gold, thallium.

Ore at Paradise Peak contains elevated abundances of Au, Ag, Bi, Sb, Pb, Tl, Hg, S and Ba \pm Sn, Mo, Te, and Se. In addition to iron sulfide (mostly marcasite), sulfate (barite) and native sulfur were abundant throughout the deposit.

Metal abundances in peripheral, argillically altered rock are essentially unchanged except that oxidized parts are

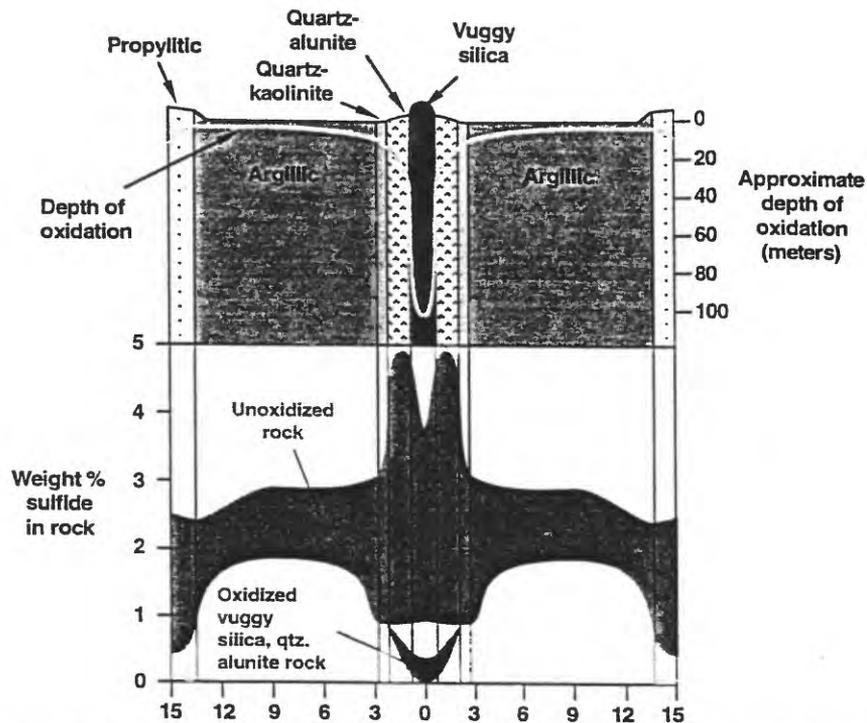


Figure 2. Schematic alteration zoning away from original fractures at Summitville, showing approximate depth of oxidation (upper plot) and range of oxidizable sulfide sulfur in sulfide minerals (lower plot). From Plumlee and others (1995a).

enriched in iron sulfide and unoxidized rocks contain gypsum and jarosite. Mineralized rock from the deepest part of this system tended to have elevated abundances of arsenic and copper but not as elevated as those characteristic of Goldfield, Nev. or Summitville, Colo.

Ore and gangue mineralogy and zonation

Minerals listed in decreasing order of abundance. Potentially acid-generating minerals underlined. In epithermal quartz-alunite gold deposits, ore deposition usually postdates development of argillic alteration.

Deep: Pyrite, chalcopryrite, tennantite, \pm wolframite-heubnerite (Julcani)

Advanced argillic, argillic alteration zones: Pyrite, enargite, covellite, chalcocite, chalcopryrite, native sulfur, marcasite, native gold, barite. Late barite, sphalerite, galena, \pm siderite (Julcani), \pm botryoidal pyrite.

Peripheral propylitic zone: Sphalerite, galena, \pm siderite, barite, \pm botryoidal pyrite

Shallow, near surface: Silica sinter, cinnabar, native mercury?, native gold, pyrite, marcasite, realgar, orpiment.

Mineral characteristics

Textures: Sulfide minerals form fine- to medium-grained (<5 mm), euhedral crystals and masses of very fine-grained, interlocking crystals. Some coarse-grained (as much as 4-5 cm) euhedral sulfide minerals also are present. Late-stage botryoidal pyrite and siderite are present in some deposits.

Trace element contents: Arsenic and antimony may be present in main-stage pyrite and (or) marcasite; late botryoidal pyrite, where present, is typically strongly enriched in arsenic, antimony, and other trace elements. Abundant stibnite-bismuthanite is the principal mineralogic site for antimony and bismuth in the Paradise Peak deposit.

General rates of weathering: Botryoidal, high trace elements > massive, fine >> coarse euhedral, low trace elements.

Secondary mineralogy

Readily soluble minerals underlined

Supergene minerals: Scorodite, goethite, limonite, K- and Na-jarosite, phosphate minerals, and plumbojarosite. Minerals formed by recent weathering: Jarosite (likely hydronium-enriched), chalcantite, brochantite, melanterite, alunogen, halotrichite, and phosphate minerals?. These minerals form by evaporation of acid water during dry periods, and then redissolve during wet periods. These minerals can also form by evaporation in overbank stream sediment downstream from mine sites.

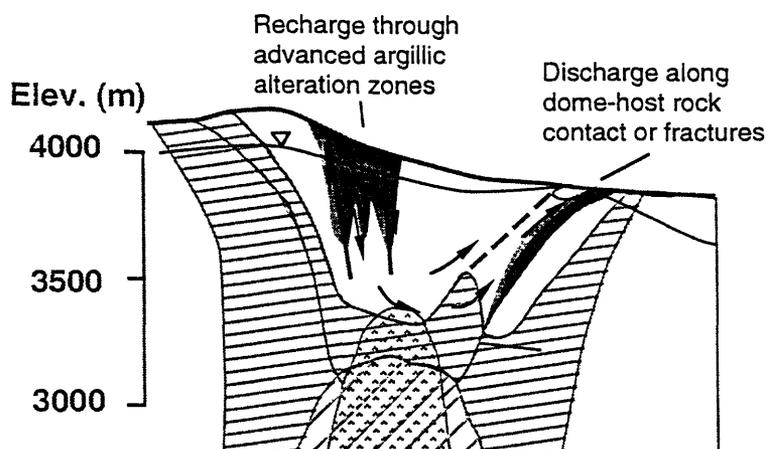


Figure 3. Inferred pre-mining hydrology at Summitville. Triangle marks position of water table.

Topography, physiography

Volcanic domes generally form topographic highs. Vuggy silica zones are resistant to weathering, and form prominent knobs and pinnacles. Because vuggy silica zones are highly resistant to weathering, physical erosion immediately surrounding clay alteration zones is minimal.

Hydrology

Pre-mining oxidation surfaces can help identify zones of high permeability within deposits. Ferricrete deposits mark pre-mining ground water discharge points. Vuggy silica alteration zones have the highest primary permeability and therefore focus ground water flow; most are oxidized to deep levels (100 meters) by pre-mining ground water. Clay alteration zones have the lowest permeability and therefore inhibit ground water flow; most are oxidized to only shallow levels (several meters to several tens of meters) by pre-mining ground water. Post-mineralization fractures can serve as conduits for ground water flow. Rock contacts between volcanic domes and surrounding rocks can be significant conduits for ground water flow and can also strongly influence distribution of alteration assemblages. In the vicinity of these deposits, the water table generally conforms to topography; the highest elevations are coincident with volcanic domes. At Summitville (fig. 3), ground water recharge is probably along vuggy silica zones. Ground water discharge prior to underground mining (marked by extensive ferricrete deposits) was primarily along contact between volcanic dome and host rocks, and at scarce locations where other fractures intersected the topographic surface of the volcanic dome. In the area around the Paradise Peak deposits, the water table is locally perched, which resulted in the presence of large blocks of unoxidized rock at shallow depths.

Mining and milling methods

Historic: Underground mine workings followed vuggy silica alteration zones in most cases. Ore was processed using stamp mills and mercury amalgamation or cyanide vat leach.

Modern: Modern operations principally involve open-pit mining of vuggy silica and surrounding clay alteration zones but include some underground mining. Ore is processed primarily using cyanide heap leach techniques.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Mine-drainage data (figs. 4 and 5): Summitville and Red Mountain Pass, Colo. (Plumlee and others, 1993; Plumlee and others 1995a,b). Mine water draining ore hosted by advanced argillic altered rocks is highly acidic and contains high to extreme dissolved metal abundances, including hundreds to several thousands of mg/l iron, aluminum, and manganese; hundreds of mg/l zinc and copper; and hundreds of $\mu\text{g/l}$ to several tens of mg/l As, Co, Ni, U, Th, Be, and REE. Water draining these deposits has elevated arsenic abundances; concentrations of uranium relative to zinc are unusual relative to those associated with many other deposit types. Preliminary data indicate that tellurium, mercury, and tungsten, though potentially enriched in advanced argillic ore, do not appear to be enriched in mine-

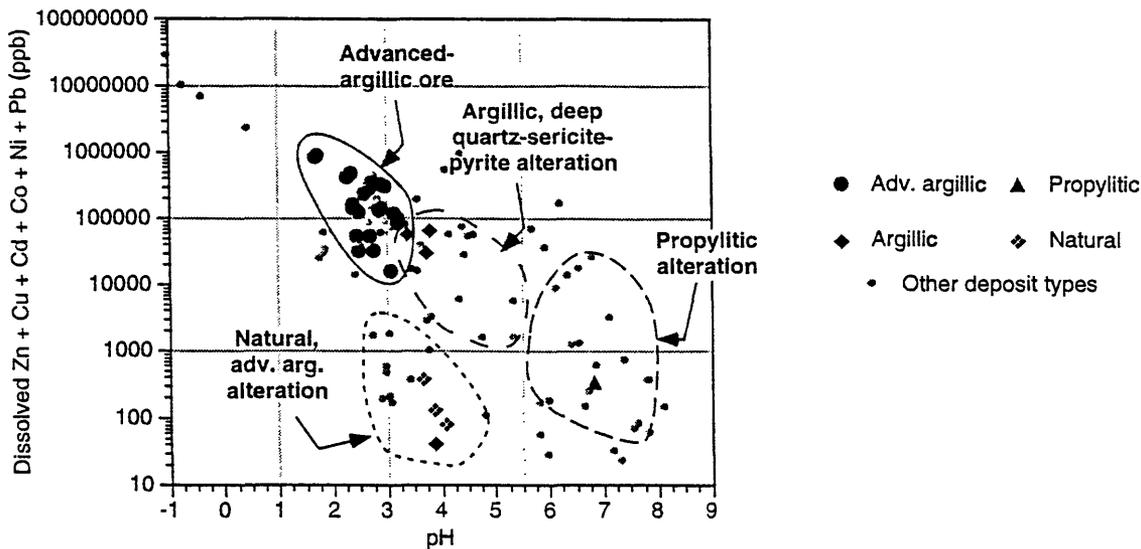


Figure 4. Plot of pH versus the sum of dissolved base metals Zn, Cu, Cd, Co, Ni, and Pb in mine and natural water draining epithermal quartz-alunite Au deposits. Lines show inferred likely ranges of metal content and pH for specific alteration zones. Samples are water draining adits and waste dumps, rain and snowmelt puddles, and seeps. Data from Koyanagi and Panteleyev (1993) and Plumlee and others (1995b).

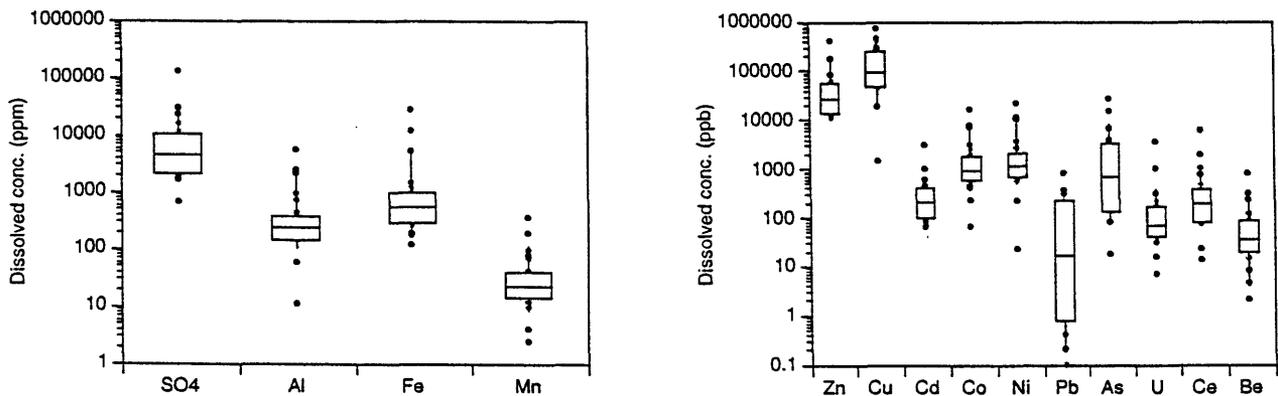


Figure 5. Box plots showing ranges of selected dissolved constituents in mine water draining ore hosted by advanced argillic alteration zones of epithermal quartz-alunite Au deposits. For each constituent, the box encloses samples falling between the 25th and 75th percentiles, the line shows the range between the 10th and 90th percentiles, and the dots show actual concentrations for samples falling outside the 25th and 75th percentiles.

drainage water. Limited data indicate that mine water draining argillic alteration zones has slightly higher pH and lower metal content.

Mine water draining shallow hot spring ore: No data available. The best currently available data are for water draining advanced-argillic, native sulfur-rich parts of a hot spring sulfur deposit (Leviathan, Calif.), which is acidic (pH 2-3) and has relatively low base metal contents but elevated abundances of arsenic, antimony, and thallium (Ball and Nordstrom, 1989).

Natural-drainage data: Limited data for a relatively wet climate with high dilution rates (British Columbia) suggest low acidity (pH between 2 and 3) and elevated dissolved metal abundances, including hundreds of mg/l iron and aluminum; abundances of copper and zinc, tens to hundreds of $\mu\text{g}/\text{l}$, are lower than those measured in mine drainages. Potentially economically recoverable elements: High copper abundances in drainage water could be economically extracted.

Metal mobility from solid mine wastes

Metals and acid are readily liberated from sulfide-mineral-bearing mine wastes due to oxidation of sulfide minerals, mainly pyrite. During dry periods, secondary soluble salts form by evaporation. During wet periods, the soluble

salts are rapidly dissolved. These salts can be present as coatings on rock material. Metal and acid are probably not liberated in significant amounts from mine wastes associated with deposits oxidized extensively prior to mining. Storm water samples: The pH and metal contents of water in rain and snowmelt puddles, which contain dissolved soluble salts, is generally similar to that of water draining adits and waste dumps (Plumlee and others, 1995b). Water-rock leaching: The results of a few leaching experiments with advanced argillic waste rock material from Summitville (50 g sample in 1 liter of distilled water, Plumlee and others, 1995b) show that metal concentrations and pH values of leach water rapidly (within tens of minutes) approach those of water draining adits and mine dumps.

Soil, sediment signatures prior to mining

No data currently available.

Potential environmental concerns associated with mineral processing

Mercury amalgamation of ore during historic mining may provide a source of mercury contamination not directly attributable to epithermal quartz-alunite gold deposits.

Cyanide geochemistry: Heap leach and other cyanide processing solutions are likely to include copper-cyanide complexes (containing as much as several hundred mg/l copper), with lesser zinc and silver cyanide complexes (present as weak cyanide complexes with as much as several tens of mg/l contained metals), and strong gold-cyanide complexes. Arsenic, cobalt, nickel, and iron may be present at low mg/l abundances in cyanide heap leach solutions. Thiocyanate (SCN⁻) abundances may be quite high in ore containing unoxidized sulfide minerals. At Summitville, degradation of cyanide accidentally released into the environment may have been enhanced by mixing with acid-mine drainage and the resulting breakdown of copper-cyanide complexes; thiocyanate likely did not degrade rapidly.

Smelter signatures

Epithermal quartz-alunite gold ore from which copper and silver were extracted during historic mining were probably smelted. No data have been identified concerning the mineralogy or chemical composition of soil affected by emissions from smelters that processed epithermal quartz-alunite gold ore. The closest analogue is Butte, Mont., where enargite-chalcocite-bornite ore from cordilleran lode deposits were smelted. There, soil proximal to smelters is very highly enriched in copper, arsenic, zinc, and lead.

Climate effects on environmental signatures

Currently available data are from moderately wet, seasonally temperate climate (Rocky Mountains). However, water draining advanced argillic ore in all climates is likely to be quite acidic and metal rich. Evaporation of acid drainage water, which leads to significant increases in metal concentrations and acidity, is important in all climates in which wet periods are interspersed with prolonged dry periods. At Summitville, evaporation has been an important process during dry Summer and Fall seasons even though total precipitation at the site exceeds 125 cm per year (Plumlee and others, 1995b). No data are available for tropical-humid, very dry, or arctic climates. Intense chemical weathering that affects exposed deposits in humid tropical climates oxidizes sulfide minerals to significant depths. Unless the area is simultaneously subjected to high rates of mechanical erosion, oxidation products isolate or reduce the underlying sulfide minerals, which inhibits continued oxidation; the potential for additional acid drainage generation is thereby limited.

Potential environmental effects

Potential downstream environmental effects of acid drainage in moderately wet to moderately dry climates can be significant in magnitude and spatial extent, especially if the surrounding geologic terrane is primarily composed of volcanic rocks with low acid buffering capacity. Predominant downstream signatures include elevated abundances of acid, iron, aluminum, manganese, and copper. Iron and aluminum form hydrous oxide precipitates as a result of dilution by downstream tributaries, and help sorb some of the dissolved metals. However, if water remains sufficiently acidic (due to limited dilution by downstream tributaries or acid generation resulting from precipitation of hydrous oxide minerals), manganese, copper, and zinc can persist (at abundances of hundreds $\mu\text{g/l}$, or more) in solution well downstream from mine sites (Smith and others, 1995).

In very wet climates, dilution may significantly reduce downstream effects. In dry or seasonally wet and dry climates, off-site drainage is greatest during short-term storm events or longer-term wet periods; reactions between this water and surrounding alkaline sediment (caliche) and soil, and with alkaline water draining the

sediment and soil, probably help mitigate acid drainage. Downstream storm water evaporation, however, may lead to the formation of acid- and metal-bearing salts that can themselves generate off-site acid drainage during storms (K. Stewart, unpub. data).

Guidelines for mitigation and remediation

- (1) Acid drainage can be successfully remediated using lime addition and sodium-bisulfide precipitation of metals (which produce acid-generating sludge). Lime addition to iron-rich drainage water may generate sufficient suspended particulates onto which a major fraction of dissolved arsenic, lead, and copper can sorb, thereby reducing or eliminating the need for sodium-bisulfide addition; in addition, wastes are non-acid-generating.
- (2) Isolation of unoxidized sulfide minerals and soluble secondary salts from oxidation and dissolution is crucial to acid drainage mitigation.
- (3) Surrounding carbonate-bearing rocks, including carbonate sedimentary rocks or carbonate-bearing propylitically altered rock on the fringes of deposits, should be carefully considered for their utility in acid-mine drainage mitigation. For example, acid water could be channelled through underground fracture systems in propylitic rock to help reduce acidity.
- (4) Cyanide heap-leach solutions should be treated by peroxide addition or other standard techniques. Heap-leach pads should be decommissioned by rinsing or bioremediation.
- (5) Mixing cyanide heap-leach solutions with acid drainage may effectively neutralize both. Acid in drainage water breaks down copper-cyanide complexes, forming volatile free cyanide and copper-iron-cyanide particulates, which degrade photolytically. Because of the alkalinity of heap-leach solutions, iron in acidic drainage precipitates as particulates, which then effectively sorb other metals contributed from acid drainage and heap-leach solutions.

Geoenvironmental geophysics

Resistivity studies can be used to identify rocks saturated with metal-bearing ground water. Porous rocks that can focus ground water flow can be identified by microgravity studies. Heat generated by sulfide mineral oxidation may have an associated thermal anomaly measurable by borehole logging or shallow probes; measures of excess heat flux can provide an approximation of total acid generation potential. Induced polarization methods can provide qualitative estimates of sulfide mineral percentages and grain size. The position, volume and mineralogy of clay bodies can be identified by induced polarization.

REFERENCES CITED

- Ashley, R.P., 1990, The Goldfield gold district, Esmeralda and Nye Counties, Nevada, *in* Shawe, D.R., Ashley, R.P., and Carter, L.M.H., eds., *Geology and resources of gold in the United States*: U.S. Geological Survey Bulletin 1857-H, p. H1-H7.
- Ball, J.W., and Nordstrom, D.K., 1989, Final revised analyses of major and trace elements from acid mine waters in the Leviathan Mine drainage basin, California and Nevada, October 1981 to October 1982: *Water-Resources Investigations*, Report No. WRI 89-4138, 46 p.
- Berger, B.R., 1986, Descriptive model of epithermal quartz-alunite Au, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models*: U.S. Geological Survey Bulletin 1693, p. 158.
- Cox, D.P., and Singer, D.A., 1986, *Mineral deposit models*: U.S. Geological Survey Bulletin 1693, 379 p.
- Deen, J.A., Rye, R.O., Munoz, J.L., and Drexler, J.W., 1994, The magmatic hydrothermal system at Julcani, Peru—Evidence from fluid inclusions and hydrogen and oxygen isotopes: *Economic Geology*, v. 89, p. 1924-1938.
- Gray, J.E., and Coolbaugh, M.F., 1994, Summitville, Colorado—Geologic framework and geochemistry of an epithermal acid-sulfate deposit formed in a volcanic dome: *Economic Geology*, v. 89, p. 1906-1923.
- Gray, J.E., Coolbaugh, M.F., Plumlee, G.S., and Atkinson, W.W., 1994, Environmental geology of the Summitville Mine, Colorado: *Economic Geology*, v. 89, p. 2006-2014.
- John, D.A., Nash, J.T., Clark, C.W., and Wulfstange, W., 1991, Geology, hydrothermal alteration, and mineralization at the Paradise Peak gold-silver-mercury deposit, Nye County, Nevada, *in* Raines, G.L., Lisle, R.E., Schafer, R.W., and Wilkinson, W.H., eds., *Geology and ore deposits of the Great Basin*, Symposium proceedings: Reno, Geological Society of Nevada and U.S. Geological Survey, p. 1020-1050.
- Koyanagi, V.M., and Panteleyev, Andre, 1993, Natural acid-drainage in the Mount McIntosh/Pemberton Hills area, northern Vancouver Island (92L/12), *in* Grant, B., and others, eds.: *Geological fieldwork 1992; a summary of field activities and current research*, Ministry of Energy, Mines and Petroleum Resources, Report No. 1993-1, p. 445-450.

- Perkins, M., and Nieman, G.W., 1982, Epithermal gold mineralization in the South Mountain volcanic dome, Summitville, CO: Denver Region Exploration Geologists Symposium on the genesis of Rocky Mountain ore deposits: Changes with time and tectonics, Denver, Colorado, Nov. 4-5, 1982, Proceedings, p. 165-171.
- Plumlee, G.S., Gray, J.E., Roeber, M.M., Jr., Coolbaugh, M., Flohr, M., Whitney, G., 1995a, The importance of geology in understanding and remediating environmental problems at Summitville, *in* Posey, H.H., Pendleton, J.A., and Van Zyl, D., eds.: Proceedings, Summitville Forum '95, Colorado Geological Survey Special Publication #38, p. 13-22.
- Plumlee, G.S., Smith, K.S., Ficklin, W.H., Briggs, P.H., and McHugh, J.B., 1993, Empirical studies of diverse mine drainages in Colorado-Implications for the prediction of mine-drainage chemistry: Proceedings, Mined Land Reclamation Symposium, Billings, Montana, p. 176-186.
- Plumlee, G.S., Smith, K.S., Mosier, E.L., Ficklin, W.H., Montour, M., Briggs, P.H., and Meier, A.L., 1995b, Geochemical processes controlling acid-drainage generation and cyanide degradation at Summitville, *in* Posey, H.H., Pendleton, J.A., and Van Zyl, D., eds.: Proceedings, Summitville Forum '95, Colorado Geological Survey Special Publication #38, p. 23-34.
- Smith, K.S., Plumlee, G.S., and Ficklin, W.H., 1994, Predicting water contamination from metal mines and mining wastes: Notes, Workshop #2, International Land Reclamation and Mine Drainage Conference and Third International Conference on the Abatement of Acidic Drainage: U.S. Geological Survey Open-File Report 94-264, 112 p.
- Smith, K.S., Mosier, E.L., Montour, M.R., Plumlee, G.S., Ficklin, W.H., Briggs, P.H., and Meier, A.L., 1995, Yearly and seasonal variations in acidity and metal content of irrigation waters from the Alamosa River, Colorado, *in* Posey, H.H., Pendleton, J.A., and Van Zyl, D., eds.: Proceedings, Summitville Forum '95, Colorado Geological Survey Special Publication #38, p. 293-298.
- Stoffregen, R.E., 1987, Genesis of acid-sulfate alteration and Au-Cu-Ag mineralization at Summitville, Colorado: *Economic Geology*, v. 82, p. 1575-1591.
- Vikre, P.G., 1989, Ledge formation at the Sandstone and Kendall gold mines, Goldfield, Nevada: *Economic Geology*, v. 84, p. 2115-2138.

EPITHERMAL MN DEPOSITS (MODEL 25g; Mosier, 1986a)

by Dan L. Mosier and David L. Campbell

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Manganese oxide concentrations are present as small veins, stringers, nodular masses, breccia-fillings, and coatings of drusy cavities in fractured, argillized or silicified, Tertiary volcanic rocks of continental origin that range in composition from rhyolite to basaltic (fig. 1).

Examples

Talamantes, Mexico; Gloryana, N. Mex.; Sardegna, Italy.

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include other epithermal gold-silver veins (Models 25b, 25c, 25d, 25e); hot spring gold-silver (Model 25a); barite veins, fluorite veins.

Potential environmental considerations

If associated with iron, elevated abundances of soluble manganese in potable water supplies may stain plumbing fixtures and laundry, and cause a foul odor or taste in water. If present at sufficient abundances, other metals, including tens of thousands of mg/l iron, trace to thousands of mg/l lead, trace to thousands of mg/l zinc, and trace to thousands of mg/l copper, that may be present in manganese ore (Wilson and Rocha, 1948; Hewett, 1964), may be present in acidic, metal-bearing water.

Exploration geophysics

Geophysical signatures for this particular deposit type have not been investigated. The lack of sulfide minerals precludes use of some geophysical methods.

References

Geology: Wilson and Rocha (1948), Hewett (1964), and Hariya (1980).
Environmental geology, geochemistry: Crerar and others (1980), Wedepohl (1980), and Abukhudair and Farooq (1989).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Deposits are small; known deposits can be as large as 1.4 million metric tons of ore containing 464,000 metric tons of manganese (Red Hill, N. Mex.); the median deposit is 0.025 million metric tons at a median grade of 30 percent manganese (Mosier, 1986b).

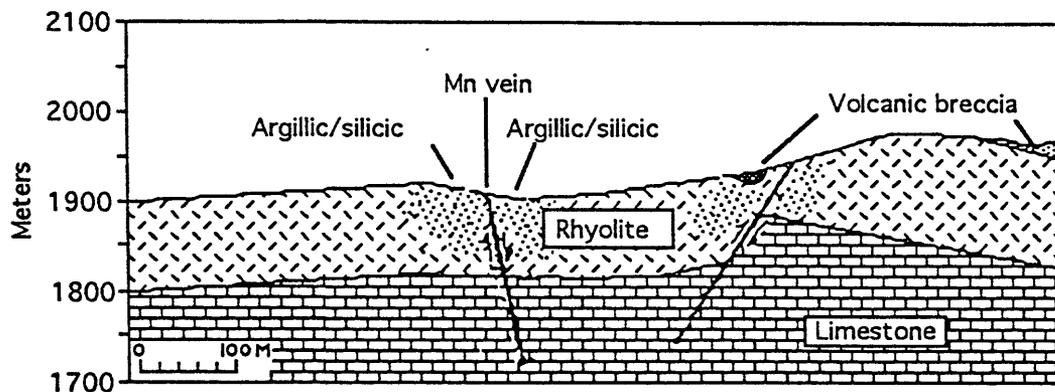


Figure 1. Schematic cross-section of a typical epithermal manganese vein in faults showing extent of argillic or silicic alteration. Modified from Wilson and Rocha (1948) showing relations at Talamantes district, Mexico.

Host rocks

Host rocks include rhyolitic, dacitic, andesitic, or basaltic flows, breccias, tuffs, and agglomerates. In most cases, manganese is more concentrated in and more rapidly leached from mafic volcanic rocks; chemical weathering causes mafic volcanic rocks to decompose more rapidly than felsic volcanic rocks.

Surrounding geologic terrane

Surrounding terrane is primarily volcanic; basement rocks may be sedimentary, metamorphic, and (or) plutonic.

Wall-rock alteration

Argillic alteration assemblages, especially those that include kaolinite, are dominant. Silicic alteration assemblages may extend over hundreds of meters along elongate zones; long axes of these altered zones may extend as much as three times the length of short axes.

Nature of ore

Ore consists of manganese oxide minerals in open-space fillings in faults, fractures, and breccias, as coatings on drusy cavities, and as stains or thin crusts on rock surfaces.

Deposit trace element geochemistry

Data for samples from the Optimo claim, Luis Lopez district, N. Mex., indicate that copper, zinc, molybdenum, tungsten, and thallium contents decrease outward in manganese crusts, whereas antimony and lead increase outward; arsenic abundances are unchanged (Hewett, 1964). Iron, barium, strontium, and phosphorous may also be present.

Ore and gangue mineralogy and zonation

Characteristic ore assemblages include psilomelane and (or) pyrolusite in calcite and quartz gangue. Ore assemblages may also include braunite, wad (hydrated manganese oxide mineral intergrowths), manganite, cryptomelane, hollandite, coronadite, ramsdellite, manganocalcite, chalcedony, opal, cristobalite, K-feldspar, barite, fluorite, gypsum, anhydrite, hematite, limonite, or zeolite. Fluorite and barite typically are present near manganese veins. Hewett (1964) observed that within a given district fluorite and barite usually extend to greater depths than manganese veins.

Mineral characteristics

Crusts of manganese oxide minerals in veins are persistently layered with psilomelane, hollandite, cryptomelane or coronadite. Psilomelane is the most widespread and abundant oxide mineral and is typically massive, sooty, and black. Hollandite, coronadite, and cryptomelane are present as distinct fibrous layers, which may be as much as 3 mm thick. Psilomelane, hollandite, and cryptomelane may be present in botryoidal forms. Less common pyrolusite and ramsdellite form layers of crystals that line drusy cavities.

Secondary mineralogy

Some manganese oxide minerals, limonite, and kaolinite may be supergene alteration products.

Topography, physiography

Most known epithermal manganese deposits are in well drained areas of moderate to high relief. Silicified rock associated with some deposits forms highs due to resistance to erosion.

Hydrology

Faults, fractures, and rock contacts are possible ground water flow channels. Underground workings down to depths of a few hundred meters also constitute water conduits. Argillic zones in adjacent altered rocks may impede or restrict water flow, whereas the highly permeable nature of some volcanic host rocks may focus flow. Enhanced permeability caused by alteration-related feldspar removal may also enhance ground water flow.

Mining and milling methods

Deposits are mined in open cuts, shafts, and adits. Mining is generally shallow, usually less than 200-m depths, and individual veins are followed for less than 1,000 m in most districts. Ore is usually concentrated by hand sorting or by jig to grades as much as 40 weight percent manganese. Concentrated ore is shipped to off-site plants.

ENVIRONMENTAL SIGNATURES

Drainage signatures

No data specifically pertaining to epithermal manganese deposits is available. More studies concerning geochemical signatures around manganese epithermal veins are required. Water and mine waste sampling and analysis of metals from many sites need to be conducted before quantified findings can be presented.

Metal mobility from solid mine wastes

Manganese oxide minerals have low solubility and normally do not represent an environmental concern. No data specific to metal mobility from epithermal manganese mine wastes are available.

Soil, sediment signatures prior to mining

Manganese is commonly present as a constituent of silicate and other minerals, as an adsorbed component on clays and humates, as colloidal organic complexes, and (or) as a constituent of most soil, in which it is present as oxide or hydroxide minerals (Crerar and others, 1980). No data specific to the geochemistry of soil near epithermal manganese deposits are available.

Potential environmental concerns associated with mineral processing

Because low grade ore is usually concentrated by hand or jig to high grades, stockpiles and waste piles of low grade material, potential sources of materials with elevated quantities of manganese or other environmentally deleterious elements, may be present at mine sites or at storage facilities. Manganese-enriched dust, which may pose health risks, may also be produced by these stockpiles and waste piles.

Smelter signatures

No data available.

Climate effects on environmental signatures

Because most epithermal manganese deposits contain low sulfide mineral abundances and because manganese oxide minerals are relatively insoluble, climatic variation probably does not significantly affect geoenvironmental signatures associated with these deposits.

Geoenvironmental geophysics

Metal-bearing ground water plumes may be traceable using geoelectric methods, including the ground slingram. Plumes containing 1,000 mg/L (or more) total dissolved metals can be detected using this method. Heavy-metal contaminated plumes are usually more conducting than ordinary ground water, particularly in the eastern and northern United States, where most ground water contains <1,000 mg/L dissolved metals. Slingrams such as the Geonics EM-31 or EM-34 give readings of greater than about 25 mS/m within 5 m of metal-charged plumes. In ideal circumstances, contaminant plumes can be rapidly outlined by sequential traverses across their edges. Silicic zones near manganese veins are characterized by very low conductivity because conductivity values decrease with increasing silica content.

REFERENCES CITED

- Abukhudair, Mohammad Y., and Farooq, Shaukat, 1989, Kinetics of ozonation of iron (II) and manganese (II) in a pure water system: *Journal of Environmental Sciences and Health*, v. 24, no. 4, pt. A, p. 389-407.
- Cox, D.P., and Singer, D.A., eds., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- Crerar, D.A., Cormick, R.K., and Barnes, H.L., 1980, Geochemistry of manganese: an overview, *in* Varentsov, I.M. and Grasselly, Gy., eds., *Geology and geochemistry of manganese*, v. 1, Stuttgart: E. Schweizerbart'sche Verlagsbuchhandlung, p. 293-334.
- Hariya, Yu, 1980, On the geochemistry and formation of manganese dioxide deposits *in* Varentsov, I.M., and Grasselly, Gy., eds., *Geology and geochemistry of manganese*, v. 1, Stuttgart, E. Schweizerbart'sche Verlagsbuchhandlung, p. 293-334.
- Hewett, D.F., 1964, Veins of hypogene manganese oxide minerals in the southwestern United States: *Economic Geology*, v. 59, no. 8, p. 1429-1472.
- Mosier, D.L., 1986a, Descriptive model of epithermal Mn, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 165.

- _____ 1986b, Grade and tonnage model of epithermal Mn, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 166-167.
- Wedepohl, K.H., 1980, Geochemistry behavior of manganese, *in* Varentsov, I.M. and Grasselly, Gy., eds., Geology and geochemistry of manganese, v. 1, Stuttgart: E. Schweizerbart'sche Verlagsbuchhandlung, p. 335-351.
- Wilson, I.F., and Rocha, V.S., 1948, Manganese deposits of the Talamantes district near Parral, Chihuahua, Mexico: U.S. Geological Survey Bulletin 954-E, p. 181-208.

RHYOLITE-HOSTED SN DEPOSITS (MODEL 25h; Reed and others, 1986)

by Eugene E. Foord, Robert A. Ayuso, Donald B. Hoover, and Douglas P. Klein

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Rhyolite-hosted tin deposits are in some multiple, overlapping, Tertiary-age flow domes (fig. 1). These deposits include cassiterite (SnO_2) and can be divided into four types: (1) sparse amounts of cassiterite in lithophysae, miarolitic cavities, and tiny gash veins, (2) in argillized zones and well-defined gash veins and anastomosing veinlets that vary widely in orientation and size, (3) in veins and stockwork-like areas of reticulate veinlets in the distal edges of rhyolite flow domes and in the underlying tuffs and ash-flow tuffs, and finally as (4) placer accumulations of "wood-tin" and crystalline cassiterite. Cassiterite was deposited in a near-surface environment characterized by extreme temperature and pressure gradients. Conditions of tin deposition vary among localities, ranging from high-temperature vapor-dominated systems to low temperature and low pressure fluid-dominated systems. The largest of these deposits are in Mexico; in the United States no deposit of this type is currently in production nor have any produced a significant quantity of ore.

Examples

"Mexican-type tin deposits", for example, those in the states of Durango and Zacatecas; Black Range tin district, Sierra and Catron Counties, N. Mex.; one locality in Thomas Range, Juab County, Utah.

Spatially and (or) genetically related deposit types

No associated deposit types (Cox and Singer, 1986) are known, but geochemistry suggests that rhyolite hosting these deposits may be the extrusive equivalent of igneous rocks that host Climax-molybdenum type deposits (Model 16).

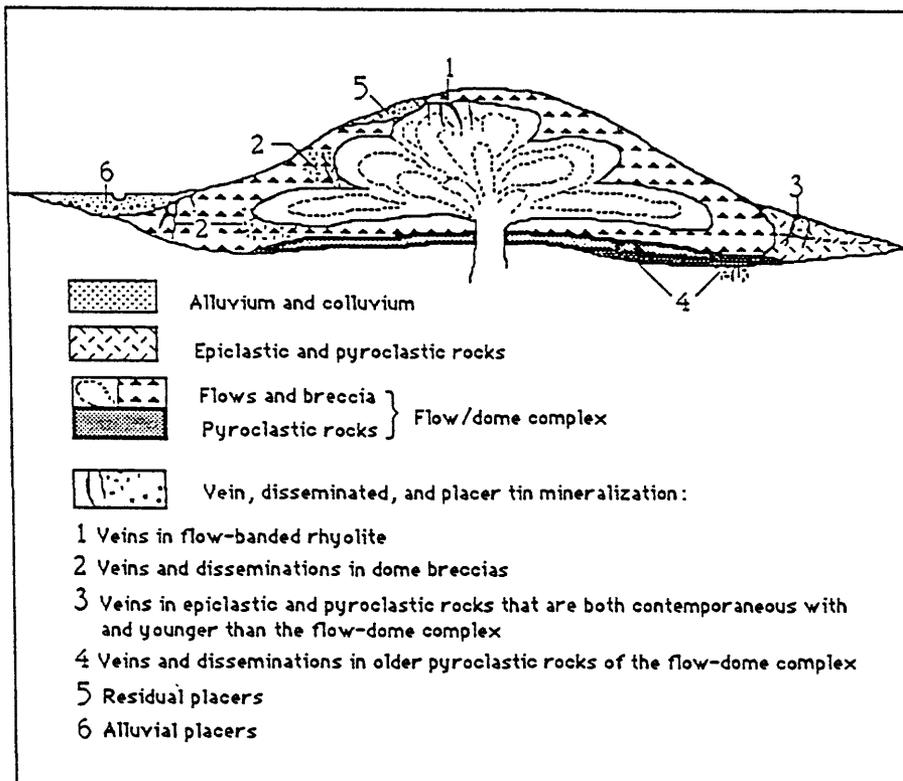


Figure 1. Diagrammatic cross section of rhyolite-hosted Sn deposit showing relationship of cassiterite concentrations to rhyolite dome (from Reed and others, 1986).

Potential environmental considerations

(1) Placer mining of known natural cassiterite concentrations in the United States and Mexico is essentially complete. Known deposits are not economically viable at the present time; in addition, small tonnages of these deposits probably preclude future economic viability. Similarly, associated low tonnage lode deposits are even less likely to be exploited. Environmental impact associated with past mining activities in the United States is limited. Acid-mine-drainage-generation potential associated with these deposits is minimal.

(2) Most old placer workings have generally been stabilized following mining activities; these present little or no environmental concern.

(3) The solubility of tin in surface water is very low; consequently it has virtually no impact on the environment.

(4) Arsenic-bearing minerals (for instance, durangite, beudantite, and hidalgoite) associated with lode, rhyolite-hosted tin deposits are rare and volumetrically minor; incorporated arsenic is present in relatively insoluble mineral phases. Thus, arsenic associated with these deposits is of limited environmental concern.

Exploration geophysics

The high radioelement content of most host rhyolites can be identified using gamma-ray methods; similarly low thermal inertia related to elevated glass content can be used to identify these rhyolites. Resistivity studies can be used to identify argillic alteration zones. Most alteration zones associated with tin-bearing rhyolite are areas of intense vapor-phase activity. Vapor-phase altered rocks have local argillic alteration overprints. Multispectral remote sensing techniques can identify mineralized or altered areas.

References

Geology: Maxwell and others (1986), Duffield and others (1990), and Rye and others (1990).

Mineralogy: Foord and others (1985), Foord and others (1989), and Foord and others (1991).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Tin-placer deposits associated with rhyolite lava domes are very small (less than 100 tons). Associated vein-type deposits are also small; some veins may be as much as 30 to 40 cm wide and extend 100 m or more. Zones of reticulate veinlets may be several thousand square meters in size. In these zones, veinlets may be spaced every few tens of centimeters to several meters and much of the intervening rock is altered and mineralized.

Host rocks

These deposits are in high-silica, metaluminous to peraluminous, rhyolite flow domes and associated pyroclastic rocks.

Surrounding geologic terrane

Rhyolite lava domes with associated tin deposits are present in large volcanic fields, as much as several thousand km², within stable, intraplate continental crust.

Wall-rock alteration

Host rocks to rhyolite-hosted tin deposits experience vapor-phase alteration that locally results in argillic assemblages; mineralized vein rock is argillically altered.

Nature of ore

Cassiterite is present as well-formed crystals in high-temperature lithophysal and miarolitic cavities, and in some small veinlets. This type of cassiterite, deposited by vapor phase processes, is characterized by anomalous contents of iron, antimony, and titanium. Low temperature, fluid-dominated, veins and veinlets contain microcrystalline cassiterite that pseudomorphs hematite. Cassiterite deposited at low temperatures and under fluid-dominated conditions is wood tin that contains minor to major amounts of indium, arsenic, zinc, silicon, and lead as well as some antimony and iron.

Deposit trace element geochemistry

Rhyolite-hosted tin deposits contain elevated abundances of Nb, Th, U, Sb, Li, As, Zn, Pb, and rare earth elements (fig. 2).

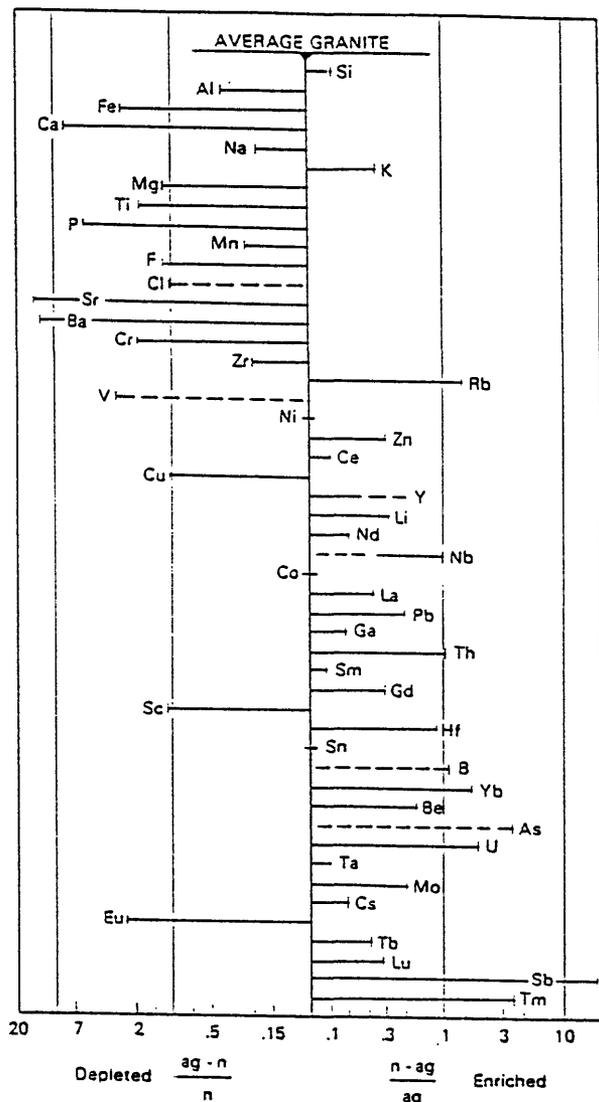


Figure 2. Diagram showing relative ratios of depletion or enrichment of elements in Taylor Creek Rhyolite compared to concentration in an average granite (Krauskopf, 1979). ag=average granite, n=average amount in Oligocene Taylor Creek Rhyolite.

Ore and gangue mineralogy and zonation

Potentially acid-generating minerals are underlined.

Type 1 deposits: cassiterite, hematite, pseudobrookite, bixbyite, braunite, topaz, quartz, cristobalite, tridymite and sanidine.

Type 2 deposits: hematite, cassiterite, quartz, fluorite, sanidine, heulandite, stilbite, chabazite, maxwellite, squawcreekite, tilasite, gasparite-(Ce), chernovite-(Y), calcite, beryl, "chernovite-(Ce)", cerianite, and others.

Type 3 deposits: quartz, hematite, sanidine, cristobalite, tridymite, cassiterite (crystalline and wood tin), durangite, beudantite, vanadinite, stolzite, calcite, hidalgoite, jarosite, alunite, opal, fluorite, smectite, cryptomelane, and todorokite.

Type 4 deposits: wood tin, varlamoffite, clay minerals.

Mineral characteristics

Cassiterite forms individual and intergrown euhedral crystals to several mm across. It is also intergrown with hematite, which it sometimes replaces. Wood tin is present in masses, as large as 4 kg, characterized by a banded and colloform layered structure.

Secondary mineralogy

Only secondary arsenate and arsenate-phosphate minerals have potentially deleterious environmental effects. Because sulfide minerals are very scarce in rhyolite-hosted tin deposits, secondary iron and manganese oxide minerals, usually produced by weathering and alteration of sulfide minerals, are also sparse.

Topography, physiography

All known rhyolite-hosted tin deposits lie in mountainous terrane with as much as several hundred meters of relief. Placer deposits are located on relatively gently sloping rhyolite domes and associated ash-flow tuff deposits. In a tropical climate, rhyolite-hosted tin deposits may have negative relief because of the rapid decomposition of rhyolite to bauxite and aluminum-rich soil.

Hydrology

Known deposits are located in a desert environment, where rainfall and consequent surface water runoff are limited. The rhyolites are very porous, permeable, and well drained.

Mining and milling methods

Cassiterite-bearing placers associated with tin-bearing rhyolite have been mined by hand. Primitive gravity separation techniques have been used to beneficiate some ore.

ENVIRONMENTAL SIGNATURES

Virtually nil. Low abundances of arsenic have been detected in water draining type 3 deposits. The climate in all known areas that contain rhyolite-hosted tin deposits is arid. Thus, potentially hazardous elements are little mobilized. Flash floods capable of significant placer deposit redistribution and widespread detrital cassiterite dissemination are rare.

Drainage signatures

Drainage basins in the principal United States and Mexican areas that contain rhyolite-hosted tin deposits contain sediment enriched in hematite, bixbyite, pseudobrookite, and cassiterite. Although specific data are lacking, rhyolite that hosts tin deposits contains elevated fluorine contents; accessory fluorite and topaz are the principal residences of fluorine in these rocks. Under some conditions, fluorine may be leached from these minerals leading to elevated concentrations in associated ground water.

Metal mobility from solid mine wastes

Metal mobility from these deposits is limited because they contain very minor quantities of sulfide minerals whose oxidation generates acid, metal-charged drainage.

Soil, sediment signatures prior to mining

Because cassiterite is resistant to mechanical and chemical degradation, soil and sediment associated with rhyolite-hosted tin deposits contains elevated tin abundances. Stream sediment collected from drainages in the Black Range, N. Mex., contain elevated abundances of Sn, B, Be, La, Pb, Y, and Zr (Steven Smith, unpub. data, 1995). Nonmagnetic heavy-mineral concentrates derived from these sediments contain elevated abundances of these elements plus Bi, Mo, Sb, W, Ti, and occasionally As. Stream sediment associated with rhyolite-hosted tin deposits in the Wah Wah Mountains, Utah, contains elevated abundances of a number of metals, including tens of ppm beryllium, tens of ppm niobium, and tens to hundreds of ppm tin; nonmagnetic heavy-mineral concentrates derived from these sediments also contain elevated abundances of some metals, including thousands of ppm tin, hundreds of ppm niobium, tens of ppm molybdenum, and, in addition, may contain thousands of ppm thorium (Detra and others, 1986; Duttweiler and Griffiths, 1989).

Potential environmental concerns associated with mineral processing

No data.

Smelter signatures

Smelting tin ore derived from rhyolite-hosted deposits could produce anomalous amounts of indium, arsenic, antimony, and possibly other metals.

Climate effects on environmental signatures

No data; however, because cassiterite is resistant to mechanical and chemical degradation and because the sulfide mineral content of rhyolite-hosted tin deposits is low, deposits of this type located in different climate regimes probably have similar, minimal environmental signatures.

Geoenvironmental geophysics

Acid water related to jarosite- or alunite-enriched areas that may be associated with rhyolite-hosted tin deposits can be identified by ground or airborne geophysical surveys. Surficial acid water produces color anomalies on airborne or satellite imagery. Subsurface acid water can produce low resistivity anomalies identifiable from resistivity surveys. Surfaces characterized by enhanced radioactivity, such as might be present in waste piles associated with rhyolite-hosted tin deposits, can be identified by gamma ray spectrometry.

Acknowledgments.--Steven M. Smith and Karen D. Kelley provided information concerning the geochemistry of stream sediment associated with rhyolite-hosted tin deposits in the Black Range, N. Mex., and Wah Wah Mountains, Utah, respectively.

REFERENCES CITED

- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- Detra, D.E., Arbogast, B.F., and Duttweiler, K.A., 1986, Analytical results and sample locality map of stream-sediment, heavy-mineral-concentrate, and rock samples from the southern Wah Wah Mountains, Utah: U.S. Geological Survey Open-File Report 86-161, 60 p.
- Duffield, W.A., Reed, B.L., and Richter, D.R., 1990, Origin of rhyolite-hosted tin-mineralization: evidence from the Taylor Creek rhyolite, New Mexico; *Economic Geology*, v. 85, p. 392-398.
- Duttweiler, K.A., and Griffiths, W.R., 1989, Geology and geochemistry of the Broken Ridge area, southern Wah Wah Mountains, Iron County, Utah: U.S. Geological Survey Bulletin 1843, 32 p.
- Foord, E.E., Hlava, P.F., Fitzpatrick, J.J., Erd, R.C., and Hinton, R.W., 1991, Maxwellite and squawcreekite, two new minerals from the Black Range Tin District, Catron County, New Mexico, U.S.A., *Neues Jahrbuch Miner. Mh.*, H.8, p. 363-384.
- Foord, E.E., Maxwell, C.H., and Hlava, P.F., 1989, Mineralogy of the Black Range Tin District, Sierra and Catron Counties, New Mexico (abs.): *New Mexico Geology*, v. 11, no. 2, 39-40.
- Foord, E.E., Oakman, M.R., and Maxwell, C.H., 1985, Durangite from the Black Range, New Mexico, and new data for durangite from Durango, and Cornwall: *Canadian Mineralogist*, v. 23, p. 241-246.
- Krauskopf, K.B., 1979, *Introduction to Geochemistry* (2nd edition): New York, McGraw-Hill, 721 p.
- Maxwell, C.H., Foord, E.E., Oakman, M.R., and Harvey, D.B., 1986, Tin deposits in the Black Range Tin District; *New Mexico Geological Society Guidebook, 37th Field Conference, Truth or Consequences*, p. 273-281.
- Reed, B.L., Duffield, Wendell, Ludington, S.D., Maxwell, C.H., and Richter, D.H., 1986, Descriptive model of rhyolite-hosted Sn, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 168.
- Rye, R.O., Lufkin, J.L., and Wasserman, M.D., 1990, Genesis of the rhyolite-hosted tin occurrences in the Black Range, New Mexico, as indicated by stable isotope studies; *Geological Society of America Special Paper 246*, p. 233-250.

LOW-TI IRON OXIDE CU-U-AU-REE DEPOSITS (MODELS 25i and 29b; Cox, 1986a,b)

by Michael P. Foose and V.J.S. Grauch

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

These deposits consist of low-titanium iron ore that contains variable amounts of copper, uranium, gold, and rare earth elements. In the past, these deposits have been separated into two discrete subgroups. Cox (1986a,b), for instance, refers to the subgroup consisting primarily of iron oxide minerals with minor apatite as volcanic-hosted magnetite deposits (Model 25i), whereas the subgroup that contains significant amounts of copper-sulfide minerals and uranium are termed Olympic Dam-type deposits (Model 29b). However, Hitzman and others (1992) have shown that both subgroups share common genetic traits and can be merged as a distinct deposit type; the geoenvironmental model presented here pertains to the merged deposit type.

Specific characteristics of this deposit type vary among deposits, but all deposits are characterized by magnetite and (or) hematite concentrations with distinctly low titanium contents (generally <2 weight percent TiO_2); in addition, most contain some copper sulfide minerals. Most deposits display evidence, including fluid-inclusions, replacement textures, coherently zoned alteration patterns, and alteration-associated veins, of a hydrothermal origin. However, the genesis of some deposits is ambiguous, and a variety of alternative origins, including magmatic emplacement involving immiscible iron-rich melts, syngenetic exhalations, and metamorphic dehydration, have been proposed.

The deposits range from conformable to crosscutting and may be found as parts of ore systems that extend more than 3 to 5 km in the vertical dimension. Data show that deeper parts of some of these ore deposits formed from hot (400 to $>600^\circ C$), magmatic ($\delta^{18}O \sim +8\%$) fluids; at more shallow levels, these deposits formed from cooler (200 - $400^\circ C$), mixed magmatic-meteoritic fluids ($\delta^{18}O \sim +1\%$) (Gow and others, 1994). Magnetite deposition and sodium-rich alteration zones predominate in the deeper (hotter) parts of these systems, whereas hematite, copper-sulfide minerals, and potassium-rich alteration are more prevalent in their shallower parts (fig. 1). Deposits are in rocks of widely variable ages, but are most abundant in Proterozoic (1.8-1.1 Ga) rocks.

Examples

Examples include the giant Olympic Dam uranium-copper-gold-silver-bearing deposit (Australia), the giant Bayan Obo rare earth element-niobium deposit (China), numerous iron deposits in the Kiruna district (Sweden), and iron

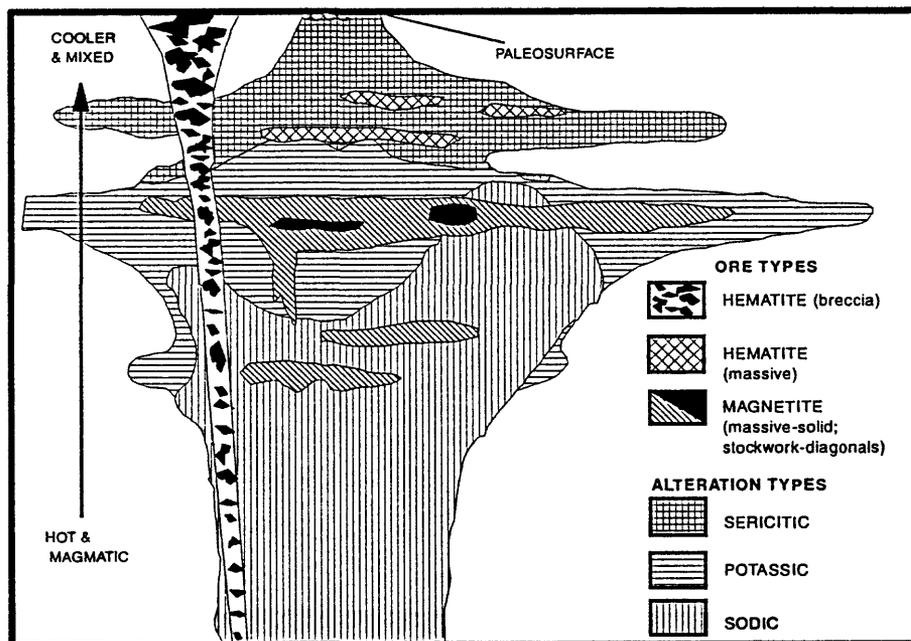


Figure 1. Generalized cross section of an idealized low-titanium iron oxide copper-uranium-gold-rare earth element deposit. Modified from Hitzman and others (1992).

deposits in Proterozoic rocks of the St. Francois Mountains (southeast Mo.) and in New York and New Jersey and in the Grenville province of New York and New Jersey. Examples in Missouri include Pea Ridge, Pilot Knob, Iron Mountain and Kratz Spring; those in New York include the Benson mines, Clifton, and Jayville; New Jersey deposits include Edison, Mt. Hope, Hibernia, Scrub Oaks, and the Hurd mine.

Spatially and (or) genetically related deposit types

None.

Potential environmental considerations

- (1) Mining copper sulfide-mineral-rich examples may generate acid drainage.
- (2) Some deposits are extremely large and development may involve ground disturbance throughout large areas.
- (3) Uranium-rich deposits may produce radon or create problems associated with elevated radiation levels.
- (4) Elevated fluorine abundances in drainage water may cause health problems, including brittle bones and tooth discoloration.

Exploration geophysics

Magnetite-rich systems can be readily recognized by aeromagnetic or ground magnetic surveys although surrounding country rocks that contain significant amounts of magnetite may complicate interpretation (for example, Kiruna area). Magnetite-dominated deposits in Missouri, for example, are associated with high-amplitude positive magnetic anomalies (Kisvarsanyi, 1981). Hematite-rich systems may have little magnetic expression. However, because both magnetite and hematite enriched rocks are much more dense than host rocks, they may be detectable by gravity surveys. Large deposits may be located on major lineaments that can be detected on satellite imagery. The unexposed Olympic Dam deposit, for example, was partly discovered because of its association with coincident positive gravity and magnetic anomalies and location on a major photolineament (Hoover and Cordell, 1992). Deposits that have high sulfide mineral content can be detected by electrical methods. Alteration zones associated with many deposits have been recrystallized during metamorphism so that they are not readily identifiable by geophysical methods.

References

Leonard and Buddington (1964), Buddington (1966), Hauck (1990), Oreskes and Einaudi (1990), Hitzman and others (1992), Gow and others (1994).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Deposits range from small to very large, but many representatives are small (less than 1 million tons). Most economic iron deposits range between 3.5 and 450 million tons, with a median value of 40 million tons. The giant Olympic Dam deposit exceeds 200 million tons. Kiruna is one of the World's eight largest iron ore producers.

Host rocks

Host rocks vary widely and may include virtually any rock type; however, most host rocks are felsic volcanic or plutonic rocks.

Surrounding geologic terrane

Most deposits are in moderate to high grade metamorphosed felsic volcanic or plutonic rocks. Typically, these rocks are associated with either a continental volcanic arc (Andean volcanic setting) or anorogenic felsic magmatism that accompanied post-tectonic extensional collapse of orogens. For example, Kiruna ore is typically associated with alkalic rhyolite, trachyte, and (or) trachyandesite. Most deposits in New York are associated with granitic gneiss principally composed of quartz and either albite or microcline. Deposits in New Jersey are associated with a series of predominantly monzonite or quartz monzonite intrusions. Most deposits in Missouri are associated with granite porphyry or iron-rich trachyte. Most of these rocks have very limited acid-buffering capacity. However, other host rock types, including carbonate rocks, that have high buffering capacity may be present.

Wall-rock alteration

Wall-rock alteration is commonly intense. Spatial alteration zonation includes, from bottom up, sodic, potassic, and

sericitic zones (fig. 1). Specific alteration assemblages depend on host rock type but commonly consist of:

Sodic alteration- magnetite + albite ± actinolite ± apatite ± chlorite.

Potassic alteration- magnetite ± hematite + apatite + potassium feldspar ± sericite ± albite ± chlorite ± biotite ± epidote ± carbonate ± barite.

Sericitic alteration- hematite + sericite ± carbonate ± barite ± fluorite.

In addition, wall rock is commonly anomalously enriched in Ba, P, F, Cl, Mn, B, K, and Na.

Subsequent metamorphism has caused the alteration assemblage associated with many deposits to be recrystallized to feldspar, pyroxene, and amphibole.

Nature of ore

Most ore consists of either magnetite, hematite, or mixtures thereof. Less commonly, ore, including that at Olympic Dam and Bayan Obo, is rich in combinations of copper sulfide minerals, uranium, and rare earth elements. Ore may be either stratiform or discordant. Magnetite-rich deposits are more commonly concordant, whereas hematite-rich deposits are commonly discordant. Magnetite-rich ore is generally equigranular. Where copper sulfide minerals are present, chalcopyrite is dominant. At Olympic Dam, however, large amounts of chalcocite and bornite are present in addition to chalcopyrite. Pyrite, in veins and disseminated in ore, is generally present in minor amounts. Uranium is in uraninite, pitchblende, and brannerite. Anomalous abundances of the rare earth elements are present in almost all deposits. At Bayan Obo, they constitute as much as 6.1 weight percent of the ore and are principally in bastnaesite, florencite, monazite, and xenotime. Other common rare earth element-bearing phases are apatite and fluorite.

Deposit trace element geochemistry

In addition to copper, uranium, and the rare earth elements, which may be important ore constituents, deposits may also contain anomalous concentrations of Ba, P, F, Cl, Mn, B, K, and Na. Some deposits also have elevated Au, Ag, Co, Ni, Te, As, Mo, and Nb abundances.

Ore and gangue mineralogy and zonation

Minerals listed in general decreasing order of abundance (potentially acid-generating minerals underlined).

Deep: Ore- magnetite, apatite, minor chalcopyrite, and pyrite. Wall rock- albite, actinolite, and chlorite.

Shallow: Ore- hematite, magnetite, copper sulfide minerals (principally chalcopyrite, possibly bornite and chalcocite), apatite, pyrite, monazite, bastnaesite, florencite, xenotime, uraninite, brannerite, and pitchblende. Wall rock- potassium feldspar, sericite, chlorite, actinolite, barite, carbonate, epidote, and biotite.

Mineral characteristics

Sulfide minerals are present in some magnetite-rich deposits, but are more common in hematite-bearing ore. Sulfide minerals are usually a minor component of most deposits and are predominantly copper or iron sulfide minerals.

Secondary mineralogy

Secondary minerals are generally not significant. Some sulfide-mineral-rich deposits have associated porphyry copper-style supergene enrichment in which secondary chalcocite has been derived from primary chalcopyrite.

Topography, physiography

Low-titanium iron oxide deposits have neither characteristic topographic nor physiographic expressions.

Hydrology

Magnetite-rich ore appears to have low porosity and permeability. Hematite-rich ore is probably more permeable and tends to form discordant bodies. No general known association exists between deposit setting and position of the ground water table.

Mining and milling methods

These deposits have been and are being mined both by underground methods and by open pitting. Active underground examples include deposits in the St. Francois Mountains, Mo., in the Kiruna district (Sweden), and at Olympic Dam (Australia). Ore at Bayan Obo (China) is open pit mined.

Subsequent to mining, most ore at Kiruna undergoes primary crushing, is processed to produce a high grade magnetite concentrate, and then pelletized. The Olympic Dam deposit produces copper, uranium, gold, and silver

by first processing ore to produce copper flotation concentrates. An acid leach is used to extract uranium from both concentrates and gangue; the concentrates are further processed by copper smelting and electrowinning to obtain copper, gold, and silver.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Information on the composition of pre- and post-mining drainage from these deposits appears to be very limited. Published environmental reports on the Olympic Dam deposit are principally concerned with water use and aquifer depletion. A report by Smith (1988) notes that water downstream from the Pea Ridge and Pilot Knob, Mo., mines has increased turbidity, that the abundance of fine-grained material in the streambed is increased, and that the benthic-invertebrate population is reduced. However, the study also notes that data are insufficient to directly link these phenomena to mining activity.

The general scarcity of reactive (sulfide) minerals suggests that most of these deposits have relatively limited acid generation capacity. However, elevated concentrations of copper and slight pH reduction may result from deposits having moderate sulfide mineral abundances; sulfide-mineral-rich systems, such as Olympic Dam, are probably capable of generating very low pH water and mobilizing significant amounts of base metals. The concentrations of uranium, radium, and radon in water are a concern because these elements are known human carcinogens. Their abundances are partly correlated with their bedrock concentrations. As a result, elevated levels of these elements may be associated with some deposits. Elevated fluorine concentrations in water, which are known to damage bone and cause tooth discoloration, may be present in water associated with some low-titanium iron deposits; however, no evidence indicates that such elevated abundances are actually present.

Metal mobility from solid mine wastes

Studies documenting the mobility of metals from solid mine waste have not been identified. Application of general, process-related studies (Ficklin and others, 1992; Plumlee and others, 1992; Plumlee and others, 1993) suggests the following:

- (1) Because deposits are in host rocks having widely different acid buffering capacity and because deposits contain significantly variable sulfide mineral abundances, acid generation and metal mobility may vary greatly.
- (2) Metal discharge from deposits hosted by high-acid-buffering-capacity rocks (carbonate rocks) is likely to be minimal, especially given the generally low sulfide mineral content of most ore. Acid and metal discharge from moderate to low-acid-buffering-capacity host rocks (feldspathic gneisses) may be substantially greater.
- (3) Most deposits contain sparse copper and iron sulfide minerals and thus have a relatively low acid generation capacity. However, ferric iron in hematite, which is commonly associated with sulfide minerals, may facilitate acid producing reactions if hematite is destabilized in the prevailing climatic regime.
- (4) Copper sulfide- and hematite-rich deposits (such as Olympic Dam) may have significant acid generation capacity. Although no data on the chemistry of water draining from the Olympic Dam deposit has been identified, metal concentrations may be similar to those characteristic of drainage water associated with porphyry copper deposits.
- (5) Water that contains high concentrations of uranium is known to be derived, in part, from uranium-enriched country rock. Therefore, deposits with elevated concentrations of uranium may generate uranium-rich water which, in turn, may present significant health hazards.
- (6) Some geologic environments generate fluorine-rich water that can damage human bones and cause tooth discoloration. Fluorine-rich water may develop in association with some deposits of this type.

Soil, sediment signatures prior to mining

The geochemical signatures of soil associated with these deposits apparently has not been documented. These deposits are characterized by elevated P, S, F, CO₂, Cu, Mo, V, Co, Na, and K abundances. Some or all of these elements may be enriched in associated soil. Titanium, chromium, and nickel abundances are depleted in most of these deposits.

Potential environmental concerns associated with mineral processing

Iron ore is generally beneficiated (gravity, magnetic, flotation, or selective flocculation) before treatment in a blast furnace. Rare earth elements and uranium are generally physically concentrated and then processed by a variety of chemical techniques. At the Olympic Dam, Australia, deposit, tailings contain elevated metal abundances, including 0.15 to 0.2 weight percent copper and 250 to 300 ppm U₃O₈, which may be a source of drainage contamination.

Smelter signatures

Copper sulfide minerals are typically smelted and may produce SO₂-rich and metal-rich emissions, which may increase acidity and foster accumulation of heavy metals in downwind areas.

Climate effects on environmental signatures

The effects of various climate regimes on the geoenvironmental signature specific to low-titanium iron oxide copper-uranium-gold-rare earth element deposits are not known. However, in most cases the intensity of environmental impact associated with sulfide-mineral-bearing mineral deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell.

Geoenvironmental geophysics

Acid or metal-bearing water, fluid movement, and active sulfide mineral oxidation can all be identified using electrical methods. Associated geochemical signatures that involve rare earth elements or radioactive minerals can be detected by spectral reflectance or gamma-ray spectral methods, respectively.

REFERENCES CITED

- Buddington, A.F., 1966, The Precambrian magnetite deposits of New York and New Jersey: *Economic Geology*, v. 61, p. 484-510.
- Cox, D.P., 1986a, Descriptive model of volcanic-hosted magnetite, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 172.
- _____, 1986b, Descriptive model of Olympic Dam Cu-U-Au, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 200.
- Ficklin, W.H., Plumlee, G.S., Smith, K.S., and McHugh, J.B., 1992, Geochemical classification of mine drainages and natural drainages in mineralized areas: *Proceedings, 7th International Water-Rock Interaction Conference, Park City, Utah, 1992*, p. 381-384.
- Gow, P.A., Wall, V.J., Oliver, N.S., and Valenta, R.K., 1994, Proterozoic iron oxide (Cu-U-Au-REE) deposits: Further evidence of hydrothermal origins: *Geology*, v. 22, p. 633-636.
- Hauck, Steven A., 1990, Petrogenesis and tectonic setting of middle Proterozoic iron oxide-rich ore deposits-an ore deposit model for Olympic Dam-type mineralization: *U.S. Geological Survey Bulletin, 1932*, p. 4-39.
- Hitzman, M.W., Oreskes, N., and Einaudi, M.T., 1992, Geological characteristics and tectonic setting of Proterozoic iron oxide (Cu-U-Au-REE) deposits: *Precambrian Research*, v. 58, p. 241-287.
- Hoover, D.B. and Cordell, L.E., 1992, Geophysical model of Olympic Dam *in* Hoover, D.B., Heran, W.D., and Hill, P.L., eds., *The geophysical expression of selected mineral deposit models: U.S. Geological Survey Open File Report 92-557*, p. 112-114.
- Kisvarsanyi, E.B., 1981, Kiruna-type iron-apatite-(copper) deposits, *in* Pratt, W.P., ed., *Metallic mineral-resource potential of the Rolla 1°x2° quadrangle, Missouri, as appraised in September 1980: U.S. Geological Survey Open-File Report 81-518*, p. 26-34.
- Leonard, B.F., and Buddington, A.F., 1964, Ore deposits of the St. Lawrence County magnetite district, northwest Adirondacks, New York: *U.S. Geological Survey Professional Paper 377*, 259 p.
- Oreskes, N., and Einaudi, M.T., 1990, Origin of rare earth element-enriched hematite breccias at the Olympic Dam Cu-U-Au-Ag deposit, Roxby Downs, South Australia: *Economic Geology*, v. 85, p. 1-28.
- Plumlee, G.S., Smith, K.S., Ficklin, W.H., and Briggs, P.H., 1992, Geological and geochemical controls on the composition of mine drainages and natural drainages in mineralized areas: *Proceedings, 7th International Water-Rock Interaction Conference, Park City, Utah, 1992*, p. 419-422.
- Plumlee, G.S., Smith, K.S., Ficklin, W.H., Briggs, P.H., and McHugh, J.B., 1993, Empirical studies of diverse mine drainages in Colorado-Implications for the prediction of mine-drainage chemistry: *Proceedings, Mined Land Reclamation Symposium, Billings, Montana*, p. 176-186.
- Smith B.J., 1988, Assessment of water quality in non-coal mining areas of Missouri: *U.S. Geological Survey Water-Resources Investigations Report 87-4286*, 50 p.

SEDIMENT-HOSTED AU DEPOSITS (MODEL 26a; Berger, 1986)

by Albert H. Hofstra, Joel S. Leventhal, David J. Grimes, and William D. Heran

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Carlin-type deposits are epigenetic, large-tonnage, low-grade, sediment-hosted disseminated gold deposits. The deposits are known mainly in northern Nevada and northwestern Utah where they are arranged in clusters and belts. The deposits in this region are estimated to contain about 5,000 tonnes of gold, more than half of which (~3100 tonnes) is in the Carlin Trend. Approximately 1,000 tonnes of gold have been produced. Carlin-type gold deposits are one of the most important types currently being mined in the western United States.

Many aspects of this geoenvironmental model also apply to distal disseminated deposits as defined by Cox and Singer (1990), Doebrich and Theodore (in press), and Howe and others (1995).

Deposit geology

Unoxidized refractory ore: Refractory ore consists of variably decalcified, dedolomitized, argillized, silicified, sulfidized, carbonaceous sedimentary rocks that contain disseminated iron, arsenic, antimony, mercury, and thallium sulfide minerals. Base-metal sulfide minerals are rare or absent in most deposits. Although pyrite, marcasite, orpiment, and realgar have high acid-generating capacity, they generally are present in small amounts (much less than 5 volume percent) and are usually disseminated in, or surrounded by, carbonate rocks with high acid-consuming capacity. Zones with 5-50 volume percent pyrite, marcasite, orpiment, or realgar are present in some deposits. Ore is refractory because much of the gold forms sub-micron grains in pyrite and marcasite and because carbon in the rock can extract gold from cyanide solutions.

Oxide ore: Natural weathering and oxidation of refractory ore cause formation of oxide ore (with low sulfide mineral and carbon contents) from which gold is recovered by cyanide heap leaching. Acid generating capacity of the surrounding carbonate rocks is low or nil, and their acid consuming capacity is high.

Jasperoid ore: Jasperoid ore is similar to refractory ore but is strongly silicified and usually lacks orpiment and realgar. Its acid-generating capacity is moderately high due to disseminated pyrite and marcasite and its acid-consuming capacity is low due to lack of carbonate minerals; however, jasperoids are usually surrounded by carbonate rocks with high acid-consuming capacity. Jasperoids are brittle and often highly fractured, which enhances permeability; in many places, they are weathered and oxidized to great depths, >300 m in a few instances, whereas surrounding rocks are generally oxidized to shallower depths. Some poorly developed jasperoid or partly silicified rocks have abundant, well-developed porosity in and near some of the largest Carlin-type systems in Nevada. Rocks adjacent to oxidized jasperoids are usually decalcified and argillized due to acid attack by supergene fluids.

Examples

The following deposits are in Nevada, unless otherwise noted: Carlin, Cortez, Getchell, Gold Acres, Gold Quarry, Jerritt Canyon, Alligator Ridge, Post-Betze, Rain, Twin Creeks, Meikle, Mercur (Utah), Ratatotok (Indonesia?), and deposits in Guizhou and Guangxi Provinces (China ?).

Spatially and (or) genetically related deposit types

Carlin-type deposits show no clear genetic relationship to other types of ore deposits. Locally, they may be present in the vicinity of volcanic-hosted precious metal deposits, epizonal pluton-related porphyry, skarn, manto, or vein deposits, syngenetic base-metal or barite deposits, or epithermal quartz-stibnite-barite veins.

Potential environmental considerations

Relative to other mineral deposit types, sediment-hosted gold deposits have relatively low potential for associated environmental concerns, especially in light of their large size. Mining activity predominantly exploits oxidized ore with negligible acid generating and high acid consuming capacities. Refractory ore is processed in mills, and its waste is collected in closely monitored tailings ponds. Environmental mitigation commonly emphasizes isolation of sulfide-mineral-rich rocks (refractory ore stockpiles) with low acid consuming capacity from weathering and oxidation. Commonly, rocks with the greatest acid generation potential and highest base-metal concentrations are unrelated to the gold deposits and coincidentally are present in the mine area. Waste rock with high acid generating and low acid consuming capacities or high base-metal concentrations is isolated from weathering and oxidation and

(or) mixed with or encased in calcareous waste rock.

Because natural ground water associated with these deposits can have elevated concentrations of Fe, Mn, As, Sb, Tl, Hg, Se, W, \pm base metals, water produced from dewatering wells may require treatment to decrease concentrations of these elements, and to decrease abundances of suspended sediment. The large size and depth of some deposits requires dewatering large volumes of rock, on the order of 0.1 to 1.0 km³ for some deposits or clusters of deposits. Substantial amounts of water, some of which is used to grow alfalfa in Nevada, are produced during mining. The temperature of ground water produced from some deposits is higher than ambient temperatures, which increases its metal transport capability.

In comparison to other deposit types, potential downstream and offsite environmental effects are of relatively limited magnitude and spatial extent; however, surface and groundwater may include elevated concentrations of one or more of the elements As, Sb, Tl, Hg, Se, W, \pm base metals. Vegetation such as sagebrush and grasses may accumulate arsenic and other elements.

Dust generated by open pit mining refractory ore, which contains elevated concentrations of sulfur, arsenic, and other elements, may be transported downwind from the mine.

Exploration geophysics

Satellite and airborne multispectral data are helpful in defining major lithologic boundaries, structural zones, and areas of hydrothermal alteration (Rowan and Wetlaufer, 1981; Kruse and others, 1988). Airborne magnetic and electromagnetic surveys can be used to delineate intrusive contacts, rock units and faults, and detect alteration (Grauch, 1988; Taylor, 1990; Grauch and Bankey, 1991; Hoover and others, 1991; Pierce and Hoover, 1991; Wojniak and Hoover, 1991).

References

Joraleman (1951), Erickson and others (1964), Erickson and others (1966), Hausen and Kerr (1968), Wells and others (1969), Wells and Mullins (1973), Radtke and others (1980), Bagby and Berger (1985), Rye (1985), Bakken and Einaudi (1986), Romberger (1986), Tafuri (1987), Cunningham and others (1988), Holland and others (1988), Bakken and others (1989), Kuehn (1989), Berger and Bagby (1990), Ilchik (1990), Leventhal and Hofstra (1990), Massinter (1990), Nelson (1990), Hofstra and others (1991), Kuehn and Rose (1992), Arehart and others (1993a,b), Maher and others (1993), Christensen (1994), Albino (1994), Hofstra (1994), Turner and others (1994), and Doebrich and Theodore (in press).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Deposits are small (100,000 metric tonnes) to large (200,000,000 metric tonnes). Grades range from 1 to 20 gm Au/t. Contained gold ranges from 1,500 Kg (50,000 oz) to 930,000 Kg (30,000,000 oz; Post-Betze, Nev).

Host rocks

Calcareous or dolomitic sedimentary rocks are the dominant host rocks for this deposit type. Ore may also be hosted by siliceous sedimentary rocks or igneous rocks.

Surrounding geologic terrane

Most deposits are hosted in Paleozoic and to a lesser extent Mesozoic miogeoclinal and eugeoclinal sedimentary rocks. Jurassic to Late Eocene calc-alkalic plutons and Eocene to Recent fluvial, lacustrine and volcanic rocks are present locally. Carlin-type deposits in Nevada and Utah are approximately coeval and cospatial with a late Eocene volcanic field, although a one-to-one spatial correspondence between the deposits and volcanic centers or plutons is absent.

Wall-rock alteration

Refractory ore: Alteration associated with refractory ore reflects progressive reaction of moderately acidic CO₂- and H₂S-rich ore fluids (pH 4 to 5) with carbonate host rocks. Inner zone-- decalcified, \pm dedolomitized, \pm argillized, \pm silicified, and sulfidized. Realgar and (or) orpiment are locally present. Narrow zones that consist predominantly of iron and (or) arsenic sulfide minerals are present in some deposits. Intermediate zone-- dolomite stable, 2m1 mica stable, partially to completely decalcified, sulfidized, \pm realgar/orpiment. Outer zone-- calcite stable, sulfidized. Jasperoid: Silicification reflects combined effects of cooling and reaction with carbonate host rocks. Boundary with unaltered carbonate rocks is gradational but very abrupt. Jasperoids are above, below, beside, or within refractory

ore zones.

Typical sulfide-mineral sulfur concentrations are <5 weight percent in refractory ore. Sulfidized and argillized intermediate to mafic igneous rocks have sulfide-mineral sulfur concentrations >10 weight percent and therefore have high acid generating and relatively low acid consuming capacities. Some deposits contain narrow zones with 10 to 50 volume percent realgar and (or) orpiment enclosed by decalcified rock that has high acid generating and low to moderate acid consuming capacities. Oxide ore is a product of supergene weathering of refractory ore and jasperoid and generally has sulfide mineral concentrations <1 volume percent.

Nature of ore

Refractory ore: Most gold resides in trace-element-rich pyrite and marcasite as sub-micron blebs. Arsenic is the major trace element in pyrite and (or) marcasite followed in decreasing abundance by antimony, thallium, and mercury. Gold also resides in orpiment, realgar, and cinnabar, on the surface of clay minerals, in or on organic carbon, and in or on quartz.

Oxide ore: Gold is present as free gold, resides in iron oxide minerals or quartz, and is adsorbed on clay minerals.

Deposit trace element geochemistry

These deposits exhibit a characteristic suite of trace elements, including silver, arsenic, antimony, mercury, thallium, and barium ± tungsten ± selenium, whose abundances are elevated.

Ore and gangue mineralogy and zonation

Minerals listed in decreasing order of abundance. Acid-generating minerals underlined. Barite is present locally.

Inner refractory ore: Quartz, ± dolomite, 2m1 mica, pyrite, marcasite, orpiment, realgar, kaolinite, illite/smectite.

Outer refractory ore: Calcite, dolomite, quartz, 2m1 mica, pyrite, marcasite.

Oxide ore: Calcite, dolomite, quartz, 2m1 mica, limonite/goethite/hematite, kaolinite, illite/smectite, relict pyrite.

Mineral characteristics

Pyrite/marcasite and arsenopyrite generally replace iron-bearing minerals and form disseminations in host rocks; they are generally fine grained and 1 mm to 1 micron in size. Late botryoidal pyrite/marcasite is present in some deposits. Most orpiment, realgar, stibnite, cinnabar, and barite are in open space along fractures and in breccias.

Secondary mineralogy

Supergene minerals include travertine, goethite, limonite, hematite, alunite, kaolinite, stibiconite, scorodite, gypsum, celestite, and phosphate minerals. Small amounts of melanterite precipitate where ground water has evaporated from mine faces in open pits.

Topography, physiography

In the Basin and Range Province of Nevada and Utah, sediment-hosted gold deposits are present at elevations between 3,000 and 1,200 m, from the crest of mountain ranges to valley margins; some are concealed by pediment gravels or alluvial valley fill. Jasperoids are resistant to erosion and commonly form bold outcrops. Because of alteration and the presence of sulfide minerals, refractory ore zones are generally more easily eroded than unaltered rocks.

Hydrology

Jasperoids are usually fractured, and therefore highly permeable, and can focus flow of oxidized ground water to great depth. Decalcified refractory ore is usually porous and permeable; rocks within and above these zones are commonly fractured or brecciated due to volume losses associated with alteration. Faults and fractures also serve as conduits for ground water flow. Brittle siliceous rocks (chert, siltite, quartz arenite) are commonly fractured, permeable, and focus ground water flow. Karst cavities and breccias, that also focus ground water flow, are present in some deposits; karst may have developed at several times between the Paleozoic and Tertiary.

Position of the water table: Water table elevation relative to the deposits has a dramatic effect on the acid generating capacity of ore. For instance, the current water table at one deposit is at a depth of ~60 m. However, associated wall rock is oxidized to a depth of ~200 m, which suggests that the paleo-water table previously extended to much greater depth. Consequently, present-day ground water is neutral to alkaline and contains low trace metal abundances. Mining this ore has little impact on water quality because the rocks are already oxidized. In contrast, mining unoxidized ore associated with many sediment-hosted gold deposits entails significant potential for

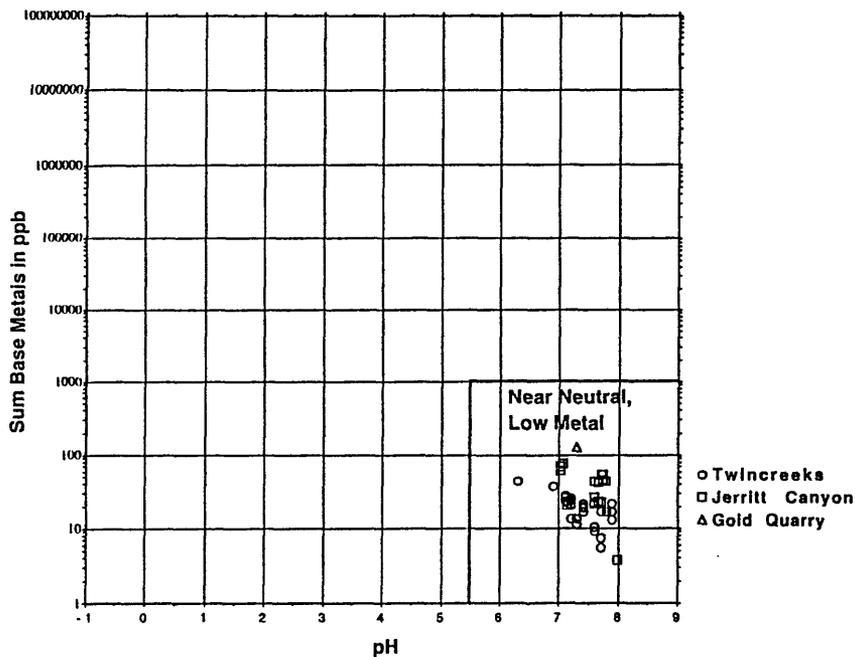


Figure 1. Ficklin plot (Ficklin and others, 1992) showing composition of natural ground water from Twin Creeks, Jerritt Canyon, and Gold Quarry, Nev., mines. All data plot within the "near neutral-low metal field."

environmental degradation. However, the overall potential for undesirable environmental impact associated with mining Carlin-type deposits is small compared to effects associated with other deposit types because these deposits have low base-metal contents and high host-rock, acid-consuming potential.

Deposits above the water table, but hosted by thick sequences of carbonaceous, pyritic, shaley eugeoclinal rocks are relatively unoxidized compared to those hosted by less carbonaceous, less pyritic calcareous miogeoclinal rocks. The eugeoclinal rocks apparently consume oxygen in descending ground water before the water table is reached.

Data for the Twin Creeks, Nev., deposit (Grimes and others, 1994; 1995) show that natural ground water, under reducing conditions below the water table, in refractory ore zones has the highest concentrations of arsenic, antimony, tungsten, manganese, iron and possibly thallium and selenium. These elements are concentrated in iron and manganese precipitates under oxidizing conditions at or above the water table.

Mining and milling methods

Historic: Oxide ore was produced from open pit mines and processed by cyanide heap leach solutions that potentially may have leaked into ground water. Refractory ore was generally avoided or stockpiled.

Modern: Oxide and refractory ore are produced from open pit and underground mines; oxide ore is processed by cyanide heap leaching. Refractory ore is oxidized using one, or a combination, of the following methods: biologic oxidation, chlorination, pressure oxidation (autoclave), or roasting. Gold is subsequently stripped from the cyanide solutions using activated carbon.

ENVIRONMENTAL SIGNATURES

Drainage signatures

The U.S. Environmental Protection Agency (EPA) chronic criteria freshwater standards most likely to be exceeded are 5.2 $\mu\text{g/l}$ cyanide, 190 $\mu\text{g/l}$ arsenic, 5 $\mu\text{g/l}$ selenium, 0.012 $\mu\text{g/l}$ mercury, 30 $\mu\text{g/l}$ antimony (proposed standard), and 40 $\mu\text{g/l}$ thallium (proposed standard). Tungsten abundances are likely to be anomalous, although no freshwater standard has been defined. In some deposits, elevated base-metal concentrations may pose a problem. The standards for these elements are as follows: 0.12 $\mu\text{g/l}$ silver, 12 $\mu\text{g/l}$ copper, 3.2 $\mu\text{g/l}$ lead, 110 $\mu\text{g/l}$ zinc, 1.1 $\mu\text{g/l}$ cadmium, 210 $\mu\text{g/l}$ chromium[III], 11 $\mu\text{g/l}$ chromium[VI], and 160 $\mu\text{g/l}$ nickel).

Mine drainage data: More work is needed to obtain and synthesize available data.

Natural stream/spring drainage data: More work is needed to obtain and synthesize available data.

Natural ground water data: Chemical analyses of natural ground water from the Twin Creeks, Jerritt Canyon and Gold Quarry, Nev., mines are shown on figures 1-2. Using the classification scheme of Ficklin and others (1992),

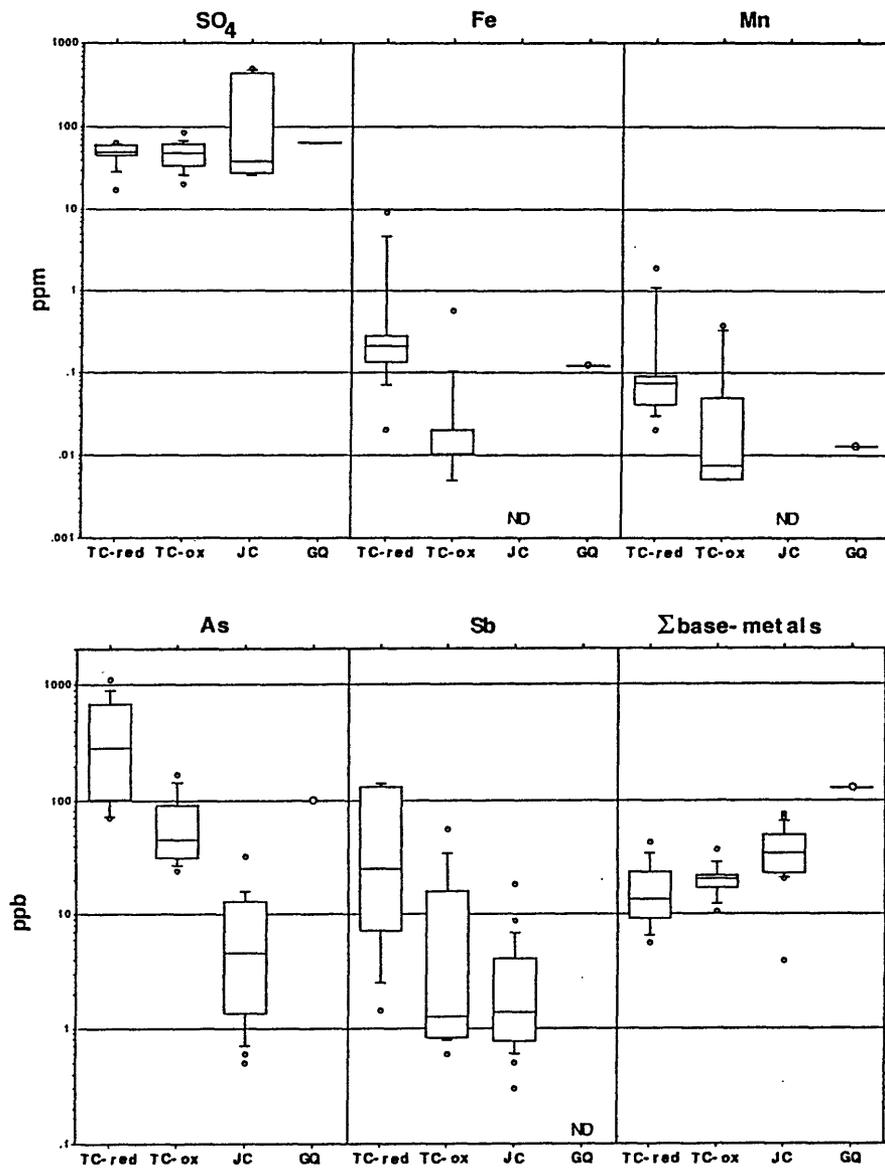


Figure 2. Bar and whisker plots showing percentile ranges of values for sulfate, iron, manganese, arsenic, antimony, and total base metals in natural ground water draining sediment-hosted gold deposits, Nev.; TC-red, Twin Creeks mine, reduced ground water; TC-ox, Twin Creeks mine, oxidized ground water; JC, Jerritt Canyon mine; GQ, Gold Quarry mine. The line in each box corresponds to the 50th percentile value. The top and bottom of each box correspond to the 75th and 25th percentile values, respectively. The whiskers extending from the top and bottom of each box correspond to values above and below the 90th and 10th percentile values.

all samples lie within the "near-neutral, low-metal field". Some samples have arsenic, antimony, selenium, or mercury concentrations that exceed EPA chronic criteria for fresh water. Concentrations of copper, lead, zinc, cadmium, nickel, and chromium are all below the EPA fresh water standard. Ground water samples from the Twin Creeks mine indicate anomalous concentrations of arsenic, antimony, tungsten (as much as 140 $\mu\text{g/l}$), iron, and manganese (Grimes and others, 1994, 1995). The highest concentrations are at sites where measured Eh indicates reducing conditions. Some elements are concentrated where alluvium is adjacent to the present-day water table. Ground water from Gold Quarry is similar to the more oxidized samples from Twin Creeks (Davis and others, in press) and contains elevated dissolved metal abundances, including 10 $\mu\text{g/l}$ thallium, 59 $\mu\text{g/l}$ selenium, and 0.4 $\mu\text{g/l}$ mercury. Arsenic concentrations in drainage water associated with Jerritt Canyon are much lower than those at Twin Creeks due to more oxidizing conditions and rocks that contain lower abundances of realgar and orpiment (Al Hofstra, unpub. data, 1995).

Metal mobility from solid mine wastes

More work is needed to obtain and synthesize available data.

Soil, sediment signatures prior to mining

More work is needed to obtain and synthesize available data.

Soil: Some soil geochemical data are available for the Getchell (Erickson and others, 1964; Brooks and Berger, 1978); Dee (Bagby and others, 1985), and Preble (Lawrence, 1986), Nev., deposits.

Stream sediment: More work is needed to obtain and synthesize available data.

Plants: Data concerning the chemistry of sagebrush growing in the vicinity of Carlin-type deposits has been published by Stewart and others (1994).

Potential environmental concerns associated with mineral processing

Heap leach and other cyanide processing solutions may contain copper, zinc, and silver complexes in addition to gold. Arsenic, cobalt, nickel, and iron may be present in low mg/l abundances in cyanide heap leach solutions. Thiocyanate (SCN⁻) abundances are highest in ore that contains unoxidized sulfide minerals.

Smelter signatures

Effluent from a few old smelters has contaminated down wind soil and vegetation. Modern operations do not involve smelting. Stack emissions from autoclaves, fluid bed roasters, chlorination circuits, etc. are monitored for compliance with federal, state, and local guidelines.

Climate effects on environmental signatures

In the Basin and Range Province of Nevada and Utah, most sediment-hosted gold deposits are in semi-arid to arid climates, although deposits in alpine settings may receive 75 to 100 cm of yearly precipitation. In the dry season, evaporation leads to formation of acid salts that dissolve during storm events or the next wet season. Surrounding carbonate rocks neutralize acid water generated during storm events.

Geoenvironmental geophysics

Ground magnetic and various electromagnetic methods may be used to map faults, fractures, and highly permeable altered zones that may serve as ground water conduits (Heran and Smith, 1984; Heran and McCafferty, 1986; Hoover and others, 1986; Hoekstra and others, 1989). Electrical resistivity methods can delineate hydrothermally altered areas and fault zones as resistivity lows and silicified rock as resistivity highs (Hallos, 1989; Hoekstra and others, 1989; Corbett, 1990). Electrical and seismic methods can be employed to determine depth to bedrock or locations of permeable and impermeable beds (Zohdy and others, 1974; Cooksley and Kendrick, 1990). Electrical methods also may be used to locate the present day water table and can delineate contaminated water plumes having significant electrical contrasts. Induced polarization surveys can be used to estimate sulfide mineral concentrations in refractory ore or in unmined or stockpiled mixed sulfide-oxide ore.

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REFERENCES CITED

- Albino, G.V., 1994, Geology and litho-geochemistry of the Ren gold prospect, Elko County, Nevada -- the role of rock sampling in exploration for deep Carlin-type deposits: *Journal of Geochemical Exploration*, v. 51, p. 37-58.
- Arehart, G.B., Eldridge, C.S., Chryssoulis, S.L., and Kesler, S.E., 1993a, Ion microprobe determination of sulfur isotope variations in iron sulfides from the Post/Betze sediment-hosted disseminated gold deposit, Nevada, USA: *Geochimica et Cosmochimica Acta*, v. 57, p. 1505-1519.
- Arehart, G.B., Foland, K.A., Naeser, C.W., and Kesler, S.E., 1993b, ⁴⁰Ar/³⁹Ar, K/Ar, and fission track geochronology of sediment-hosted disseminated gold deposits at Post/Betze, Carlin Trend, northeastern Nevada: *Economic Geology*, v. 88, 622-646.
- Bagby, W.C. and Berger, B.R., 1985, Chapter 8, Geologic characteristics of sediment-hosted, disseminated precious metal deposits in the western United States: *Reviews in Economic Geology*, v. 2, p. 169-202.

- Bagby, W.C., Pickthorn, W.J., and Goldfarb, R.J., 1985, Pathfinder elements in soils over the Dee disseminated gold deposit, Elko County, Nevada: U.S. Geological Survey Circular 949, p. 1.
- Bakken, B.M. and Einaudi, M.T., 1986, Spatial and temporal relations between wall rock alteration and gold mineralization, main pit, Carlin gold mine, Nevada, U.S.A.: in Macdonald, A.J., ed., Proceedings of Gold '86, an International Symposium on the Geology of Gold: Toronto, Canada, p. 388-403.
- Bakken B.M., Hochella, M.F. Jr., Marshall, A.F., and Turner, A.M., 1989, High-resolution microscopy of gold in unoxidized ore from the Carlin mine, Nevada: Economic Geology, v. 84, p. 171-179.
- Berger, B.R., 1986, Descriptive model of carbonate-hosted Au-Ag, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 175.
- Berger, B.R., and Bagby, W.C., 1990, The geology and origin of Carlin-type gold deposits, *in* Foster, R.P., ed., Gold Metallogeny and Exploration: Blackie and Son Ltd, Glasgow, Scotland, p. 210-248.
- Brooks, R.A. and Berger, B.R., 1978, Relationship of soil mercury values to soil type and disseminated gold mineralization, Getchell mine area, Humboldt County, Nevada: Journal of Geochemical Exploration, v. 9, p. 183-194.
- Christensen, O.D., editor, 1994, Gold deposits of the Carlin Trend, Nevada: Society of Economic Geologists Guidebook Series, v. 18, 112 p.
- Cooksley, J.W. and Kendrick, P.H., 1990, Use of seismic geophysics in the detection of epithermal precious metal deposits in the western U.S.: Explore-The Association of Exploration Geochemists Newsletter, no. 67, p. 1-4.
- Corbett, J.D., 1990, Overview of geophysical methods applied to precious metal exploration in Nevada: Seminar on Geophysics in Gold Exploration, sponsored by Geological Society of Nevada and SEG mining Committee, p. 1-21.
- Cox, D.P., and Singer, D.A., 1990, Descriptive and grade-tonnage models for distal disseminated Ag-Au deposits--A supplement to U.S. Geological Survey Bulletin 1693: U.S. Geological Survey Open-File Report 90-282, 7 p.
- Cunningham, C.G., Ashley, R.P., Chou, I., Zushu, H., Chaoyuan, W., and Wenkang, L., 1988, Newly discovered sedimentary rock-hosted disseminated gold deposits in the Peoples Republic of China: Economic Geology, v. 83, p. 1462-1467.
- Davis, A., Kempton, J.H., Nicholson, A., Moomaw, C., Travers, C., Zimmerman, C., in press, The chemogenesis of the Gold Quarry pit lake, Eureka County, Nevada: Reviews in Economic Geology.
- Doeblich, J.L., and Theodore, T.G., in press, Geologic history of the Battle Mountain Mining District, Nevada, and regional controls on the distribution of mineral systems, *in* Geology and Ore Deposits of the American Cordillera-A Symposium: Reno, Nevada, Geological Society of Nevada, U.S. Geological Survey, and Sociedad de Chile, Proceedings volume.
- Erickson, R.L., Marranzino, A.P., Oda, U., and Janes, W.W., 1964, Geochemical exploration near the Getchell mine, Humboldt, County, Nevada: U.S. Geological Survey Bulletin 1198-A, 26 p., 2 pl.
- Erickson, R.L., Van Sickle, G.H., Nakagawa, H.M., McCarthy, J.H., Jr., and Leong, K.W., 1966, Gold geochemical anomaly in the Cortez district Nevada: U.S. Geological Survey Circular 534, 9 p.
- Ficklin, W.H., Plumlee, G.S., Smith, K.S., and McHugh, J.B., 1992, Geochemical classification of mine drainages and natural drainages in mineralized areas: Proceedings 7th International Symposium on Water-Rock Interactions, Park City, Utah, p. 381-384.
- Grauch, V.J.S., 1988, Geophysical tools for defining covered features: significance for disseminated gold deposits in Nevada, USA [ext. abs.]: Geological Society of Australia, Bicentennial Gold '88, p. 527-529.
- Grauch, V.J.S. and Bankey, Vicky, 1991, Preliminary results of aeromagnetic studies of the Getchell disseminated gold deposit trend, Osgood Mountains, north-central Nevada, *in* Raines, G.L., Lisk, R.E., Schafer, R.W., and Wilkinson, W.H., eds., Geology and ore deposits of the Great Basin, Volume 2: Geological Society of Nevada, p. 781-791.
- Grimes, D.J., McHugh, J.B., and Meier, A.L., 1994, Chemical analyses of major, minor, and trace elements including gold and arsenic species, As(III) and As(V), in water samples from Kelley Creek Valley, Humboldt County, Nevada: U.S. Geological Survey Open-File-Report 94-135, p. 19.
- Grimes, D.J., Ficklin, W.H., Meier, A.L., and McHugh, J.B., 1995, Anomalous gold antimony, arsenic, and tungsten in ground water and alluvium around disseminated gold deposits along the Getchell Trend, Humboldt County, Nevada: Journal of Geochemical Exploration, v. 52, p. 351-371.

- Hallof, P.G., 1989, The Use of CSMAT method to map subsurface resistivity structures in gold exploration in Nevada [abs.]: Abstract to poster at SEG Annual Meeting, Dallas.
- Hausen, D.M., and Kerr, P.F., 1968, Fine gold occurrence at Carlin, Nevada, *in* Ridge, J.D., ed., *Ore Deposits of the United States, 1933-1967, The Graton-Sales Volume: The American Institute of Mining, Metallurgical, and Petroleum Engineers, inc., New York, Ch. 46, p. 908-940.*
- Heran, W.D., and McCafferty, A.M., 1986, Geophysical surveys in the vicinity of Pinson and Getchell mines, Humboldt County, Nevada: U.S. Geological Survey Open-File Report 86-432, 40 p.
- Heran, W.D., and Smith, B.D., 1984, Geophysical surveys at the Getchell and Preble disseminated gold deposits, Humboldt County, Nevada: U.S. Geological Survey Open-File Report 84-795, 79 p.
- Hoekstra, P., Hild, J., and Blohm, M., 1989, Geophysical surveys for precious metals exploration in the Basin-and Range, Nevada, *in* Bhappo, R.B., and Harden, R.J., eds., *Gold Forum on Technology and Practices--World Gold '89: Society of Mining Engineering, Proceedings, p. 69-75.*
- Hofstra, A.H., 1994, Geology and genesis of the Carlin-type gold deposits in the Jerritt Canyon district, Nevada: Boulder, University of Colorado, Ph.D. dissertation, 719 p.
- Hofstra, A.H., Leventhal, J.S., Northrop, H.R., Landis, G.P., Rye, R.O., Birak, D.J., and Dahl, A.R., 1991, Genesis of sediment-hosted disseminated gold deposits by fluid mixing and sulfidization: Chemical-reaction-path modeling of ore-depositional processes documented in the Jerritt Canyon district, Nevada: *Geology, v. 19, p. 36-40.*
- Holland, P.T., Beaty, D.W., and Snow, G.G., 1988, Comparative elemental and oxygen isotope geochemistry of jasperoid in the northern Great Basin; evidence for distinctive fluid evolution in gold-producing hydrothermal systems: *Economic Geology, v. 83, p. 1401-1423.*
- Hoover, D.B., Grauch, V.J.S., Pitkin, J.A., Krohn, M.D., and Pierce, H.A., 1991, Getchell trend airborne geophysics--An integrated airborne geophysical study along the Getchell Trend of gold deposits, north-central Nevada, *in* Raines, G.L., Lisk, R.E., Schafer, R.W., and Wilkinson, W.H., eds., *Geology and ore deposits of the Great Basin, Volume 2: Geological Society of Nevada, p. 739-758.*
- Hoover, D.B., Pierce, H.A., and Merkel, D.C., 1986, Telluric traverse and self potential data release in the vicinity of the Pinson mine, Humboldt County, Nevada: U.S. Geological Survey Open-File Report 86-341, 26 p.
- Howe, S.S., Theodore, T.G., and Arehart, G.B., 1995, Sulfur and oxygen isotopic compositions of vein barite from the Marigold mine and surrounding area, north-central Nevada: Applications to gold exploration [abs.]: *Geology and Ore Deposits of the American Cordillera Symposium, Reno/Sparks, Nevada April 10-13, 1995, Program with Abstracts, p. A39.*
- Ilchik, R.P., 1990, Geology and geochemistry of the Vantage gold deposits, Alligator Ridge-Bald Mountain mining district, Nevada: *Economic Geology, v. 85, p. 50-75.*
- Joraleman, P., 1951, The occurrence of gold at the Getchell mine, Nevada: *Economic Geology, v. 46, p. 276-310.*
- Kruse, F.A., Hummer-Miller, Susanne, and Watson, Ken, 1988, Thermal infrared remote sensing of the Carlin-disseminated gold deposits, Eureka County, Nevada, *in* Bulk Mined Precious Metal Deposits of the Western United States: Symposium Proceedings of the Geological Society of Nevada, p. 734.
- Kuehn, C.A., 1989, Studies of disseminated gold deposits near Carlin, Nevada: Evidence for a deep geologic setting of ore formation: State College, Pennsylvania State University, Ph.D. thesis, 395 p.
- Kuehn, C.A., and Rose, A.R., 1992, Geology and geochemistry of wall-rock alteration at the Carlin gold deposit, Nevada: *Economic Geology, v. 87, p. 1697-1721.*
- Lawrence, W.W. Jr., 1986, Sampling, geochemical, and statistical methods for soil geochemical surveys in the exploration for sediment-hosted, disseminated gold deposits; the Preble gold deposit as an example: Boulder, University of Colorado, M.S. thesis, 127 p.
- Leventhal, J.S. and Hofstra, A.H., 1990, Characterization of carbon in sediment-hosted disseminated gold deposits, north central Nevada, *in* Hausen, D.M., Halbe, D.N., Petersen, E.U., and Tafuri, W.J., eds., *Gold '90, Proceedings of the Gold '90 Symposium: Society for Mining, Metallurgy, and Exploration, Inc., Littleton, CO, p. 365-368.*
- Maher, B.J., Browne, Q.J., and McKee, E.H., 1993, Constraints on the age of gold mineralization and metallogenesis in the Battle Mountain-Eureka mineral belt, Nevada: *Economic Geology, v. 88, p. 469-478.*
- Masinter, R.A., 1990, Geology, wall-rock alteration and mineralization of the Gold Bar Deposit, Eureka County, Nevada: Stanford, Stanford University, M.S. thesis, 256 p.
- Nelson, C.E., 1990, Comparative geochemistry of jasperoids from Carlin-type gold deposits of the western United States, *Journal of Geochemical Exploration, v. 36, p. 171-195.*

- Pierce, H.A., and Hoover, D.B., 1991, Airborne electromagnetic applications-Mapping structure and electrical boundaries beneath cover along the Getchell Trend, Nevada, *in* Raines, G.L., Lisle, R.E., Schafer, R.W., and Wilkinson, W.W., eds., *Geology and ore deposits of the Great Basin, Symposium Proceedings*, p. 771-780.
- Radtke, A.S., Rye, R.O., and Dickson, F.W., 1980, Geology and stable isotope studies of the Carlin gold deposit, Nevada: *Economic Geology*, v. 75, p. 641-672.
- Romberger, S.B., 1986, Ore deposits #9. Disseminated gold deposits: *Geoscience Canada*, v. 13, p. 23-31.
- Rowan, L.C., and Wetlaufer, P.H., 1981, Relation between regional lineament systems and structural zones in Nevada: *American Association of Petroleum Geologists Bulletin*, v. 65, no. 8, p. 1414-1432.
- Rye, R.O., 1985, A model for the formation of carbonate-hosted disseminated gold deposits based on geologic, fluid inclusion, geochemical, and stable isotope studies of the Carlin and Cortez deposits, Nevada, *in* Tooker, E.W., ed., *Geologic characteristics of sediment- and volcanic-hosted disseminated gold deposits--search for an occurrence model: U.S. Geological Survey Bulletin 1646*, p. 35-42.
- Stewart, K.C., McKown, D.M., and Fey, D.L., 1994, Analytical results from a greenhouse study of sagebrush grown in soils contain Carlin ore: *U.S. Geological Survey Open-File-Report 94-0237*, 14 p.
- Tafari, W.J., 1987, *Geology and geochemistry of the Mercur mining district, Toole County, Utah*: Salt Lake City, University of Utah, Ph.D. thesis, 180 p.
- Taylor, R.S., 1990, Airborne EM resistivity applied to exploration for disseminated precious metal deposits: *Geophysics--The leading edge of exploration*, February 1990, p. 34-41.
- Turner, S.J., Flindell, P.A., Hendri, D., Hardjana, I., Lauricella, P.F., Lindsay, R.P., Marpaung, B., and White, G.P., 1994, Sediment-hosted gold mineralization in the Ratatotok district, North Sulawesi, Indonesia: *Journal of Geochemical Exploration*, v. 50, p. 317-336.
- Wells, J.D., Stoiser, L.R., and Elliott, J.E., 1969, Geology and geochemistry of the Cortez gold deposit, Nevada, *Economic Geology*, v. 64, p. 526-537.
- Wells, J.D. and Mullins T.E., 1973, Gold-bearing arsenian pyrite determined by microprobe analysis, Cortez and Carlin gold mines, Nevada: *Economic Geology*, v. 68, p. 187-201.
- Wojniak, W.S., and Hoover, D.B., 1991, The Getchell Gold Trend, northwestern Nevada--Geologic structure delineated by further exploration of electromagnetic data collected during helicopter survey [abs.]: *U.S. Geological Survey Circular 1062, 7th Annual McKelvey Forum*, p. 77.
- Zohdy, A.A.R., Eaton, G.P., and Mabey, D.R., 1974, *Techniques of water resource investigations of the United States Geological Survey, application of surface geophysics to ground water investigations, Book 2, Chapter D1*, 116 p.

ALMADEN HG DEPOSITS (MODEL 27b; Rytuba, 1986)

by James J. Rytuba and Douglas P. Klein

INTRODUCTION

Environmental concerns related to mining and processing Almaden-type mercury deposits consist primarily of: mercury contamination of soil and plants from mine smelters because of mercury vapor and dust released during ore processing, mercury degassing from contaminated soil at mine sites and from undisturbed deposits, and potential for acid mine drainage and toxic metal release into drainage basins. These deposits typically are extremely high grade; central parts of deposits can contain more than 20 weight percent mercury. As a result, extremely high concentrations of mercury are present in residual soil where these deposits are exposed at the surface. Mercury released into creeks and rivers may contaminate lakes, estuaries, and bogs; subsequently methylmercury (CH_3Hg^+) may form and become highly concentrated through biomagnification in fish, and eventually in any animals that consume fish. For humans, most toxicity concerns related to mercury pertain to consumption of contaminated fish. However, ambient mercury vapor pressure in underground mercury mines may allow direct mercury ingestion through breathing. Also, direct ingestion of mercury contaminated soil can pose a health threat among children.

The global atmospheric mercury cycle contributes mercury to drainage basins and lakes through both wet and dry depositional processes that are mediated by leaf uptake of mercury by plants (Mason and others, 1994). The potential flux of mercury to the environment from mercury deposits and mine sites must be evaluated in the context of its flux from the global mercury atmospheric cycle. The primary natural sources of mercury to the atmosphere include the oceans, soil degassing, volcanoes, and geothermal systems (Varekamp and Buseck, 1986; Mason and others, 1994). Anthropogenic sources of mercury to the atmosphere are primarily from coal combustion, waste incineration, and smelters (Nriagu and Pacyna, 1988). Since the beginning of industrialization in about 1850, the atmospheric mercury concentration increased until about 1970, and then has decreased moderately. The mercury increase is reflected in the sedimentary record of lakes, estuaries, and bogs; recently deposited sediment from all these environments record an increase in mercury concentration of about two to five times over baseline mercury concentrations established prior to industrialization (for example see, Verta and others, 1990; and Hurley and others, 1994).

Mercury concentrations in soil associated with Almaden-type deposits can be extremely high and elevated summer temperatures can increase rock and soil degassing rates. Native mercury contained in ore also enhances degassing. Plants on or adjacent to these deposits may play an important role in mediating mercury vapor flux. Mercury is taken up by plants primarily through leaves, rather than through the root system, and fixed at the site of plant uptake. Thus, high ambient-air mercury concentrations cause plants to uptake and concentrate mercury in their leaves, and conversely, low ambient air mercury concentrations cause plants to give off mercury through their leaves (Lindberg and others, 1992). In mine areas where ambient air concentrations of mercury are elevated, due either to roasting mercury ore or from natural degassing of mercury from either contaminated (see Lindberg and others, 1995) or naturally anomalous soil (Lindberg and others, 1979), plant communities concentrate mercury in their leaves. Wash off and litter fall from these plant communities may redistribute mercury into creeks and lakes.

The formation of methylmercury is favored by the presence of ionic mercury, low pH, and high dissolved organic carbon and sulfate. Mercury methylation is a co-metabolic reaction; sulfate reducing bacteria are the most important mediators in the biotic methylation process (Campeau and Bartha, 1985; Summers, 1986). Acid mine water that has a high sulfate concentration may develop at a mercury mine site or at a naturally oxidizing mercury ore deposit. Introduction of acid water to a bog or lake may enhance methylation. Nearly all methylmercury is formed in lakes where most of it resides in fish. In lakes and estuaries, detrital particles such as clays capture Hg^{++} from the water by absorption; sedimentation of these particles inhibits methylation. Similarly, tailings that enter surface water may aid methylmercury removal from the water column and enhance sequestration in sediment.

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Deposits are generally large (10 to 100 million metric tonnes of ore containing about 2 to 20 weight percent Hg); the Almaden, Spain, deposit is the single largest mercury deposit in the world and it has been mined continuously for more than 2,000 years. The deposits essentially contain only mercury as an economically recoverable metal, and consist of massive cinnabar and native mercury replacement bodies hosted in quartzite and tuff breccias, submarine

mafic to intermediate composition pyroclastic flows, mafic dikes, and organic-rich black shales. Cinnabar-bearing veins and veinlets are present primarily as gash fractures developed during regional metamorphism of these deposits (Rytuba and others, 1988). Native mercury is present in all deposits and is the primary mineral in deposits, such as in the Las Cuevas deposit, hosted in submarine tuffs. All of these deposits are spatially associated with mafic submarine vent complexes that consist of mafic dikes and sills, oval craters typically with dimensions of 300 m by 150 m (Hernandez, 1985), and submarine calderas, such as at the Las Cuevas deposit (Rytuba and others, 1988). Megabreccia composed of black shale blocks, as much as 100 m in maximum dimension and contained in a tuff matrix, are interstratified with caldera filling lithic tuffs. Tuff breccias that fill the craters consist primarily of sedimentary wall rocks with lesser amounts of ultramafic and plutonic igneous clasts. Juvenile magma clasts within the craters are typically alkali basalt. Replacement deposits hosted in quartzite consist of stratiform zones of cross cutting mineralized rock composed of cinnabar, native mercury, pyrite, calcite, and quartz. Ore zone grades and thicknesses are highest near crater margins and decrease systematically away from crater margins.

Examples

Almaden, El Entredicho, Nueva Concepcion, Las Cuevas; Spain (Hernandez, 1985; Saupe, 1990).

Spatially and (or) genetically related deposit types

These deposits form in the early phase of near-craton, submarine basin rifting; they are closely associated with mafic, submarine vent complexes. Although back-arc volcanogenic massive sulfide deposits form in this geologic environment, none have been identified in areas adjacent to these deposits.

Potential environmental considerations

The primary geoenvironmental concerns associated with these deposits are the potential for mercury vapor release from furnaces and retorts as well as from soil and rock degassing; mercury abundances in soil, water, and vegetation may be elevated above baseline concentrations established by the global atmospheric mercury flux. Acid mine drainage may result from oxidation and dissolution of pyrite in altered shale and pyroclastic rocks that host ore. Carbonate minerals are minor gash fracture fillings and have limited acid drainage buffering capacity.

Direct introduction of mercury from these deposits into ground water may result from native mercury oxidation and dissolution but mercury from cinnabar is minor because of cinnabar's low solubility and weak oxidation under ambient conditions. Introduction of mercury into the environment primarily results from its release into the atmosphere during ore roasting and from soil and rock degassing at mine sites and undisturbed deposits. When high mercury concentrations prevail, it is efficiently absorbed from the atmosphere by plants through their leaves; mercury is concentrated in plant foliage and root uptake is minor. Wash off from plants and dry deposition of leaf litter to the forest floor are the primary routes for mercury introduction into water and soil. Methylation of mercury in bog and lake environments is enhanced by increased mercury concentrations as well as by sulfate that may be generated during pyrite oxidation.

Exploration geophysics

No geophysical investigations of this deposit type are known, however certain inferences may be drawn from surveys of deposits with similar geologic relations. Aeromagnetic anomalies may delineate mafic vent complexes with which these deposits are spatially associated. Remote sensing images can be used to identify limonite and iron oxide minerals that develop due to pyrite oxidation. Cinnabar is resistive but native mercury is highly conductive; both have very high specific gravity, near 8 gm/cm³. Almaden type deposits can probably be identified by detailed gravity surveys because they are large and contain elevated abundances of high density mercury minerals. Resistivity lows and induced polarization highs are probably associated with these deposits because of their elevated native mercury abundances. Resistivity surveys may aid identification of cinnabar deposits because of the association between conductive carbonaceous rock (black shale) and these deposits. Regional airborne or ground electrical surveys may help delineate the extent of conductive, shallow-marine-basin black shale and altered volcanic rocks that host these deposits. Induced polarization traverses may further refine the distribution of rocks that contain abundant pyrite.

References

Rytuba (1986), Saupe (1990), and Mason and others (1994).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

The deposits are typically large and contain more than 10 million metric tonnes. The deposits are clustered in stratigraphic units deposited within the same submarine basin. Most deposits have been mined by underground methods but one deposit is mined by open pit methods; the visual impact related to mining these deposits is relatively limited except for large associated tailings (calcine) piles.

Host rocks

Most deposits are hosted in quartzite and mafic to intermediate composition pyroclastic and intrusive rocks. Organic rich shale and siltstone are locally important host rocks, especially where shale is in contact with pyroclastic rocks.

Surrounding geologic terrane

Surrounding terranes typically do not contain carbonate rocks or other acid buffering alteration assemblages.

Wall-rock alteration

Pyroclastic and intrusive rocks are argillically and carbonate altered. Ultramafic xenoliths within sills and dikes are altered to carbonate-bearing mineral assemblages. Strontium isotopes indicate that intrusive and volcanic rocks have interacted extensively with sea water. Quartzite displays secondary overgrowths of quartz although silicification is not pervasive. Pyrite comprises from about 2 to 6 volume percent of pyroclastic rocks. Carbonate vein assemblages are present primarily in gash fractures.

Nature of ore

Most orebodies are massive replacement bodies that are stratiform in quartzite and form more irregular replacement orebodies in pyroclastic and intrusive rocks. Orebodies in mafic dikes and sills consist of tabular to irregular replacement masses localized at the terminations of dikes or along the upper parts of sills. Very high grade ore composed of cinnabar commonly is present at contacts between black shale and pyroclastic and intrusive rocks. Where black shale clasts are absent, native mercury is the dominant ore mineral in pyroclastic-hosted orebodies. In quartzite-hosted orebodies, ore is present near the top of the units. Discrete veins and breccia bodies are present, but most veins fill gash fractures developed during low grade regional metamorphism.

Deposit trace element geochemistry

In addition to mercury, the trace element geochemistry of the ore is very simple. Of the common ore-related elements, only iron is present in anomalous amounts; abundances of metals typically associated with mercury, 1 to 13 ppm arsenic and 0.2 to 1.6 ppm antimony, are low. In quartzite-hosted orebodies, light rare earth element abundances are elevated as a consequence of the primary trace element content of heavy minerals in quartzite. In volcanic-hosted deposits localized within caldera structures, base-metal concentrations, including as much as 50 ppm lead and as much as 80 ppm copper, are somewhat anomalous. Zinc abundances, which are typically less than 50 ppm in sediment-hosted orebodies, are as high as 4,600 ppm in volcanic-hosted deposits.

Ore and gangue mineralogy and zonation

Primary ore minerals are cinnabar and native mercury; native mercury is more common in orebodies hosted by pyroclastic rocks. Veins of barite and native mercury are peripheral to the ore zone. Volcanic and intrusive rocks are altered to a carbonate assemblage. Stratiform pyrite beds are above quartzite-hosted ore.

Mineral characteristics

Cinnabar is generally fine grained, about 0.2 to 6 mm, in replacement orebodies but is typically coarser grained, as much as 2 cm, in gash fractures. Mercury globules as much as several millimeters wide are present in host rocks; during mining operations, these may become concentrated in globules as much as several centimeters wide. Pyrite ranges from 1 to 10 mm in maximum dimension.

Secondary mineralogy

In near-surface parts of deposits, pyrite is exposed to weathering, which results in limonite and iron oxide formation. Cinnabar and native mercury are not affected by weathering process because of their low solubilities under ambient conditions and reducing conditions associated with the black shale.

Topography, physiography

Where cut by volcanic craters, orebodies are associated with resistant ledges of quartzite. Where quartzite ledges are interrupted by craters, the area of the craters is topographically more subdued.

Hydrology

Increase in hydrologic head during wet periods results in ground water fluid flow along regional structures that control the location of craters and dikes.

Mining and milling methods

Individual deposits are generally large and most mines are underground operations involving open-stope mining of high grade, stratiform orebodies. Waste rock, only a small fraction of which is brought to the surface, is used to back fill underground workings. High grade ore zones have sharp contacts with low grade ore. High grade orebodies exposed in the near-surface have been mined by open pit methods.

Ore has been processed in large retorts in the past, but most recent operations use several types of furnaces. Condensing systems that cool vapor from the furnaces in order to separate liquid mercury from other stack gases are complex multiple-pipe condensers. The furnaces include Herreshoff and rotary furnaces. Rotary furnaces consist of a rotating, inclined iron cylinder into which ore is continuously fed and from which calcine is removed. Mercury vapor and other gases are drawn from the cylinder into a condenser. The Herreshoff furnace consists of a series of circular hearths into which ore is continuously fed and mechanically advanced to successive higher temperature hearths. Calcine is removed from the base and gases are fed through a dust collector and then a condensing system. Calcium carbonate may be used to aid mechanical coagulation of finely condensed mercury particles from soot on a steam table.

Mercury has been typically bottled in 76-pound flasks at the retort or furnace site; inefficiencies in this process have caused mercury contamination of mill sites and calcines. More recently the metric-ton flask has been used.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Data that characterize drainages have not been published. The presence of associated acid mine drainage has not yet been reported.

Metal mobility from solid mine wastes

Sulfide minerals in ore are oxidized during roasting so that calcines have a distinctive red color related to iron oxide minerals in the calcine. In this highly oxidizing environment, iron is readily leachable. Mercury in calcine is present as native mercury as well as a variety of mercury oxychloride and sulfate minerals that are readily solubilized.

Soil, sediment signatures prior to mining

Mercury abundances in soil range from one to several thousand ppm and may reach several thousand ppm directly over exposed orebodies. Other trace metal abundances are not anomalous in soil, except those of zirconium, which range from 200 to greater than 1,000 ppm, and nickel, which range from 50 to 150 ppm. Base-metal concentrations in soil, including <100 ppm lead and <50 ppm copper and zinc, are low. Sediment signatures prior to mining have not been published.

Potential environmental concerns associated with mineral processing

Mine tailings, commonly termed calcine, consist of the rock aggregate generated after the mercury ore has been processed by roasting in a retort or furnace to remove mercury. Mercury recovery during ore retorting ranges from 90 to 95 percent, which results in calcine that may contain 5 to 10 percent of the mercury originally present in the ore. During the roasting process, pyrite is oxidized to iron oxide minerals giving the calcine dumps their characteristic red color.

Mercury abundances in calcine ranges from ten to several thousand ppm depending on the efficiency of the retorts and furnaces used. Calcine adjacent to the condensing pipes where mercury was recovered and bottled into flasks may have very high mercury content because mercury was commonly spilled in this area and was absorbed by iron oxide coatings on calcine fragments. Calcine in these areas may contain as much as several thousand ppm mercury.

Calcine was commonly used as road metal on unpaved roads surrounding mercury districts. This may be a problem in the case of calcine that was contaminated by mercury during the recovery process. Introduction of tailings particles into creeks is a concern because native mercury may be oxidized and along with mercury oxychloride and sulfate minerals can be methylated in aqueous environments. The fine grained nature of calcine also increases water turbidity.

Smelter signatures

Large retorts and more efficient rotary and Herschhoff type furnaces have been used to process ore from these deposits. Prior to the 1970s, significant amounts of elemental mercury as vapor, ionic mercury complexed as a chloride or sulfate, and mercury adhering to particulates were vented to the atmosphere. Elevated ambient air concentrations of mercury result in increased wet and dry deposition of mercury and leaf uptake by plants downwind from smelter sites. These processes result in elevated mercury concentrations in soil, water, and, through wash off and litter fall, to the forest floor. SO₂ released to the atmosphere during ore roasting may increase acid and sulfate concentrations in water, which in turn enhance mercury methylation.

Climate effects on environmental signatures

In wet climates conducive to plant growth, mercury degassing from soil is minimized by plant leaf mercury uptake. However, oxidation and dissolution of pyrite increase the potential for acid mine drainage generation in wet climates. Formation of sulfate minerals and derivation of organic carbon from plants enhance mercury methylation by sulfate reducing bacteria in wet climates. In dry climates, soil gas emission of elemental mercury may be important especially during high temperature seasons; this process may increase the area affected by elevated mercury if adjacent plant communities uptake mercury in their leaves through both wet and dry deposition of mercury.

Geoenvironmental geophysics

Pyrite oxidation and dissolution, which can result from weathering Almaden type mercury deposits, may produce conductive acid water that can be detected using electromagnetic, direct current resistivity, and probably induced polarization methods. Ground penetrating radar can detect acid ground water at depths of less than a few meters. Information concerning the change of fluid properties, such as resistivity, with varying concentrations of mercury ions or compounds is not available. Similarly, remote sensing reflectance variations of vegetated areas in which mercury uptake has been variable has not been documented; however, these subjects should be investigated.

REFERENCES CITED

- Compeau, G.C., and Bartha, R., 1985, Sulfate reducing bacteria: principal methylators of mercury in anoxic estuarine sediment: *Applied Environmental Microbiology*, v. 50, p. 498-502.
- Hernandez, A., 1985, Estructura y genesis de los yacimientos de mercurio de la zona de Almaden: Unpub. resumen de tesis doctoral, University Salamanca, 64 p.
- Hurley, J.P., Krabbenhoft, D.P., Babiarz, C.L., and Andren, A.W., 1994, Cycling of mercury across the sediment-water interface in seepage lakes, *in* Baker, A., ed., *Environmental chemistry of lakes and reservoirs: American Chemical Society Series No. 237*, p. 425-449.
- Lindberg, S.E., Jackson, D.R., Huckabee, J.W., Janzen, S.A., Levin, M.J., and Lund, J.R., 1979, Atmospheric emission and plant uptake of mercury from agricultural soils near the Almaden mercury mine: *Journal of Environmental Quality*, v. 8, p. 572-578.
- Lindberg, S.E., Kim, K., Meyers, T.P., and Owens, J.G., 1995, Micrometeorological gradient approach for quantifying air/surface exchange of mercury vapor: tests over contaminated soils: *Environmental Science and Technology*, v. 29, no. 1, p. 126-135.
- Lindberg, S.E., Meyers, T.P., Taylor, G.E., Turner, R.R., and Schroeder, W.H., 1992, Atmosphere-surface exchange of mercury in a forest: results of modeling and gradient approaches: *Journal of Geophysical Research*, v. 97, no. D2, p. 2519-2528.
- Mason, R.P., Fitzgerald, W.F., and Morel, F.M.M., 1994, The biogeochemical cycling of elemental mercury: Anthropogenic influences: *Geochimica et Cosmochimica Acta*, v. 58, no. 15, p. 3191-3198.
- Nriagu, J.O., and Pacyna, J.M., 1988, Quantitative assessment of worldwide contamination of air, water and soils by trace metals: *Nature*, v. 333, p. 134-139.
- Rytuba, J.J., 1986, Descriptive model of Almaden Hg, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 180.

- Rytuba, J.J., Rye, R.O., Hernandez, A.M., Deen, J.A., and Arribas, A., Sr., 1988, Genesis of Almaden-type mercury deposits: Almaden, Spain, 28th International Geologic Congress Abstracts with Program, p. 2-741.
- Saupe, Francis, 1990, Geology of the Almaden mercury deposit, Province of Ciudad Real, Spain: *Economic Geology*, v. 85, p. 482-510.
- Summers, A. O., 1986, Organization, expression, and evolution of genes for mercury resistance: *Annual Reviews of Microbiology*, v. 40, p. 607-634.
- Varekamp, J.C., and Buseck, P.R., 1986, Global mercury flux from volcanic and geothermal sources: *Applied Geochemistry*, v. 1, p. 65-73.
- Verta, M., Mannio, J., Iivonen, P., Hirvi, J.P., Jarvinen, O., and Piepponen, S., 1990, Trace metals in Finnish headwater lakes-effects of acidification and airborne load, *in* Kauppi and others, eds., *Acidification of Finland*, p. 883-908.

SILICA-CARBONATE HG DEPOSITS (MODEL 27c; Rytuba, 1986)

by James J. Rytuba and M. Dean Kleinkopf

INTRODUCTION

Environmental concerns related to mining and processing of silica-carbonate mercury deposits consist primarily of: mercury contamination of soil and water from mine waste rock and tailings (calcine), mercury vapor released during ore processing, and acid mine drainage and toxic metal release into drainage basins. Mercury released into lakes and bogs may become methylated and methylmercury (CH_3Hg^+) may become highly concentrated through biomagnification in fish and animals that consume fish. The mercury concern for humans is primarily related to consumption of contaminated fish.

See Rytuba and others (preceding model, this volume) for a discussion of global mercury budgets, cycling, and processes.

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Deposits are generally small (0.1 to 10 million metric tonnes of ore containing 0.2 to 0.8 weight percent mercury) and consist of cinnabar-bearing veins and veinlets and massive cinnabar replacement bodies developed within serpentinite that is hydrothermally altered to a silica-carbonate assemblage. Some orebodies are hosted in argillically altered shale and siltstone adjacent to silica-carbonate altered serpentinite. Orebodies are localized along regional faults, which cut tabular, serpentinized ophiolite bodies, and along the base of these tabular bodies. Impermeable serpentinite channels focus the flow of hydrothermal fluids resulting in extensive silica-carbonate alteration of serpentinite for several kilometers along contacts with adjacent country rock. Large orebodies are present in hinge regions of anticlinal structures where hydrothermal fluids are trapped below impermeable shale and silica-carbonate altered serpentinite. Mercury vapor derived from organic-rich sedimentary rocks as a result of elevated regional heat flow reacts with H_2S in the gas-rich cap in anticlinal structures to form large silica-carbonate mercury deposits. Where structural traps are absent, silica-carbonate altered serpentine contains only small mercury deposits or anomalous concentrations of mercury. Because vapor transport is an important process in these deposits, only metals that can be transported in a vapor phase are concentrated in these deposits; exceptions include metals such as nickel and chromium that are remobilized from the serpentinite by hydrothermal fluids. The hydrothermal fluid that forms these deposits is low temperature ($<120^\circ\text{C}$) and characterized by high concentrations of CO_2 - CH_4 - H_2S -petroleum (Peabody and Einaudi, 1992; Sherlock and others, 1993) that reflects its derivation from an evolved connate water (Donnelly-Nolan and others, 1993). This connate water was generated during the early stage of elevated regional heat flow (Rytuba, 1995). Very young deposits, such as those at the Elgin and Turkey Run mercury deposits, Calif., have active associated geothermal gas and hot springs.

Examples

New Almaden (Bailey and Everhart, 1964), Aetna (Yates and Hilpert, 1946), Knoxville (Sherlock and others, 1993), Culver-Baer (Peabody and Einaudi, 1992); Calif.

Spatially and (or) genetically related deposit types

These deposits are present along major structures and form during the early stage of elevated regional heat flow. They may subsequently be overprinted by higher temperature, hot-spring type gold-mercury-antimony deposits as the regional thermal anomaly reaches a maximum and near-surface volcanic activity develops. The McLaughlin, Calif., hot-spring gold-mercury deposit, which overprinted earlier formed silica-carbonate mercury deposits of the Knoxville district (Rytuba, 1995), exemplifies this process.

Potential environmental considerations

The primary geoenvironmental concerns from these deposits are potential acid mine drainage and release of mercury with the result that mercury abundances in soil, water, and (or) vegetation may be elevated above baseline concentrations established by the global atmospheric mercury flux. The potential for acid mine drainage derives from oxidation and dissolution of pyrite and marcasite in silica-carbonate altered rock that hosts the orebodies as well as from extensive areas of silica-carbonate alteration extending beyond ore zones. In some districts, altered rock extends

as much as several kilometers beyond the outer limits of ore. Carbonate minerals in the silica-carbonate alteration zone partially mitigate associated acid generation.

Direct introduction of mercury into water from these deposits is minimal since the primary ore mineral, cinnabar, is relatively insoluble and is not readily oxidized under ambient, near-surface conditions. Mine water draining deposits that contain native mercury may have elevated mercury concentrations. Introduction of mercury into the environment is primarily from release of mercury into the atmosphere when ore is retorted. When atmospheric mercury concentrations are elevated, plants uptake mercury through their leaves and mercury is concentrated in plant foliage. Wash off from plants and dry deposition of leaf litter to the forest floor is the primary route for introduction of mercury into water and soil. Methylation of mercury in bog and lake environments is enhanced by increased mercury concentrations as well as by sulfate generated during oxidation of pyrite and marcasite.

Exploration geophysics

Remote sensing techniques can identify serpentinite by infra red reflectance, thermal properties, and botanical anomalies. The sparse and unusual vegetation developed on serpentinite and its silica-carbonate altered equivalent is prominent on remote-sensing images. Aeromagnetic highs delineate serpentinite bodies and serpentinite in fault zones, particularly small deposits located along regionally extensive fault zones. Magnetic surveys may have limited utility in identification of serpentinite developed from carbonate rocks, most of which have low initial iron contents. Because cinnabar and native mercury have high specific gravity, large deposits may be detected by detailed gravity surveys. Because mercury is highly conductive, deposits that contain high concentrations of native mercury, may be associated with resistivity lows and induced polarization highs.

References

Geology: Rytuba (1986), and Rytuba and Miller (1994).
Environmental geology, geochemistry: Varekamp and Buseck (1986), Nriagu and Pacyna (1988), Lindberg and others (1992), and Hurley and others (1994).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Deposits are typically small and contain less than 10 million metric tonnes; many deposits are less than 0.1 million metric tonnes. Deposits are clustered along major structures and because silica-carbonate alteration typically extends for several kilometers beyond deposits, areas significantly larger than the ore deposit site may be impacted. Most deposits have been mined by underground methods. Visual impact is relatively limited at rare open pit mines because tailings piles, except those associated with the largest deposits, are small.

Host rocks

Shale and siltstone are locally important host rocks where they form impermeable cap rocks in anticlinal structures.

Surrounding geologic terrane

Deposits are primarily localized along the base of serpentinitized ophiolite bodies, serpentinite diapirs, and serpentinite tectonically emplaced along regional fault zones. Surrounding terranes typically do not contain carbonate rocks nor alteration assemblages with significant acid-buffering capacity. Most deposits are Tertiary, formed near the surface, and have surficial expressions of geothermal activity such as gas vents and hot springs. As a result, elevated abundances of mercury may be present in soil and sediment deposited at the time of ore deposition.

Wall-rock alteration

The silica-carbonate assemblage consists of a central core of quartz + opal + chalcedony + magnesite + dolomite + calcite + marcasite + pyrite that grades outward into a magnesite + magnetite + calcite + dolomite assemblage and then finally into serpentinite + magnetite. Pyrite and marcasite in the sulfidized central core of the alteration assemblage comprise from about 2 to 10 volume percent and are the only important acid generating sulfide minerals present. The carbonate assemblage may partially buffer acid generated by sulfide mineral oxidation. In the upper part of these deposits an advanced argillic alteration zone that consists of kaolinite + alunite + cristobalite + sulfur may be present; most often this alteration assemblage has been removed by erosion. Pyrite and marcasite in this alteration assemblage may be oxidized and contribute to acid mine drainage generation.

Nature of ore

Ore bodies are variable in character. Most consist of tabular to irregular replacement masses but discrete veins and breccia bodies are common; more rarely, stockwork veins are present. Repeated post ore movement along controlling fault zones causes development of blocks (phacoids) of very high grade cinnabar within fault gouge. In vein and breccia ore bodies, marcasite and more rarely stibnite are present. Most replacement ore bodies are monomineralic; they consist of cinnabar and minor native mercury.

Deposit trace element geochemistry

Within the ore zone, trace elements, in decreasing order of importance, include 0.1 to 1,000 ppm antimony, 10 to 3,000 ppm nickel, 600 to 5,000 ppm chromium, 2 to 100 ppm tungsten, and 1 to 12 ppm thallium. Arsenic abundances are typically very low, less than 2 ppm, in these deposits. Base metal concentrations, less than 10 ppm lead, less than 100 ppm copper, and less than 50 ppm zinc, are similarly low.

Ore and gangue mineralogy and zonation

Primary ore minerals are cinnabar and native mercury and more rarely in the oxidized, near surface environments more soluble mercury oxychloride, sulfate, and silicate minerals are present. Pyrite and marcasite are the main gangue minerals.

Mineral characteristics

Most cinnabar, about 0.2 mm, is very fine grained in replacement ore bodies but in rare cases is coarser grained in veins. Pyrite and marcasite are coarser grained and typically range from 0.5 to 5 mm.

Secondary mineralogy

Near surface exposures of deposits and alteration zones expose pyrite and marcasite to weathering, which results in formation of limonite and other iron oxide minerals. Cinnabar and native mercury are not typically affected by weathering process because of their low solubilities under ambient conditions. However, under extreme oxidizing and acid pH conditions mercury sulfate and oxychloride minerals may form as coatings on surface exposures. These yellow and green minerals are photosensitive and rapidly turn black when exposed to the sun. As a result, these minerals can be easily misidentified as manganese oxide minerals. Small amounts of mercury silicate and chromate minerals may also be present; these, along with mercury sulfate and oxychloride minerals, are more readily solubilized than cinnabar and native mercury.

Topography, physiography

Ore bodies are associated with large zones of silica-carbonate alteration that typically form resistant ridges with sparse vegetation. Adjacent serpentinite also has sparse vegetation. Altered serpentinite has a distinctive red-brown color due to the presence of iron oxide minerals. Deposits are generally exposed at or near the surface and are along regional structures that may extend for tens of kilometers.

Hydrology

Increased hydrologic head during wet periods results in ground water flow along the regional structures that control the location of silica-carbonate alteration and ore deposits. Adjacent serpentinite bodies serve as impermeable aquitards that focus ground water flow along contacts between altered and fresh serpentinite.

Mining and milling methods

Individual deposits are generally small but in most cases, several deposits are localized along the same regional fault zone. Most mines are underground operations in which high grade pockets and ore shoots have been exploited by open stope mining. Waste rock, only a small fraction of which is brought to the surface, is used to backfill underground workings. High grade ore zones have sharp contacts with low grade ore. Because low grade ore is only rarely mined, stopes tend to follow the outline of high grade ore bodies and are irregular in shape. Near-surface ore bodies have been mined by open pit methods.

See Rytuba and Klein (this volume) for a discussion of methods used to extract mercury from ore.

Mercury has been typically bottled in 76 pound flasks at the retort or furnace site. Inefficiencies in this process have caused mercury contamination of mill sites and calcines. More recently the metric ton flask has been used.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Acid mine water has a pH of 1 to 4 and precipitates amorphous iron hydroxide that selectively absorbs mercury from the water; these precipitates may contain as much as 20 ppm mercury. Elevated concentrations of as much as 670 ppm nickel and 200 ppm chromium, may also be present in these precipitates. Acid mine water may contain 100 to 1,000 mg/l iron and 0.1 to several $\mu\text{g/l}$ mercury. Acid mine water draining deposits that include stibnite may contain 1 to 10 mg/l antimony but base-metal concentrations as well as abundances of chemical precipitates are low.

In active geothermal water associated with recently formed deposits, very high tungsten concentrations range from 1 to 10 mg/l; in stream water as much as several kilometers downstream from deposits, elevated tungsten concentrations range from 260 to 680 $\mu\text{g/l}$ (Rytuba and Miller, 1994). Mercury and iron concentrations, 0.2 to 2.7 $\mu\text{g/l}$ and 0.05 to 1.4 mg/l, respectively, in unfiltered stream water are usually higher than in filtered water. However, these abundances return to baseline concentrations, 0.2 $\mu\text{g/l}$ mercury and 500 $\mu\text{g/l}$ iron, within several kilometers of mercury deposits and (or) geothermal sites (Janik and others, 1994).

Metal mobility from solid mine wastes

Sulfide minerals in ore are oxidized during roasting, which causes calcines to have a distinctive red color attributable to contained iron oxide minerals. In this high Eh environment iron is readily leachable and associated metals such as antimony, arsenic, and thallium may be mobilized as well. Mercury in calcine is native mercury and a variety of mercury oxychloride and sulfate minerals that are readily solubilized.

Soil, sediment signatures prior to mining

Mercury abundances in soil range from 10 to 100 ppb and may reach several ppm directly over exposed orebodies. Stream sediment samples from drainages in mineralized areas contain 2 to 200 ppm mercury. Stream sediment samples from drainage basins with young deposits and active geothermal systems contain 0.3 to 141 ppm mercury, 1.2 to 17.4 ppm antimony, and 8.3 to 20.3 ppm arsenic (Janik and others, 1994). Heavy mineral concentrates from streams that drain areas near deposits contain elevated metal concentrations, including as much as 4,400 ppm mercury, 10,000 ppm barium, 7,000 ppm chromium, 150 ppm copper, 500 ppm nickel, 200 ppm lead, 300 ppm tin, and 500 ppm zinc.

Potential environmental concerns associated with mineral processing

In tailings and waste dumps pyrite and marcasite are susceptible to oxidation and acid water may develop.

Mine tailings, commonly termed calcine, consist of the rock aggregate generated after mercury ore has been processed by roasting in a retort or furnace to remove mercury. Mercury recovery during retorting ranges from 90 to 95 percent, which results in calcine that may contain from 5 to 10 percent of the mercury originally present in the ore. During roasting, pyrite and marcasite are oxidized to iron oxide minerals, which gives calcine dumps their characteristic red color. The amount of mercury removed from small mines is extremely variable so that calcines associated with these operations may contain significant mercury.

Mercury abundances in calcine range from 10 to 1,500 ppm depending on the efficiency of the retorts used. Abundances of other trace metals, such as nickel and chromium, originally present in elevated concentration in ore, range from 100 to 5,000 ppm. Calcine adjacent to condensing pipes where mercury was recovered and bottled in flasks may have mercury contents of as much as several thousand ppm because mercury was commonly spilled in this area and absorbed by iron oxide coatings on calcine fragments.

Calcine was commonly used as road metal on unpaved roads surrounding mercury districts. This may be a problem in the case of calcine that was contaminated by mercury during the recovery process. Introduction of tailings particles into creeks is a concern because native mercury and mercury oxychloride and sulfate minerals can be methylated in aqueous environments. The fine grained nature of the calcine also increases water turbidity.

Smelter signatures

Several different types of retorts and condensing pipes have been used to recover mercury. These range from relatively small, inefficient single and double pipe retorts at small mines to very efficient Herschhoff type retorts at larger mines. In most cases prior to the 1970s, significant amounts of elemental mercury vapor and ionic mercury complexed as a chloride or sulfate were vented to the atmosphere. Elevated ambient air concentrations of mercury result in increased leaf uptake of mercury by plants downwind from retort sites and in elevated mercury concentrations in soil through wash off and litter fall to the forest floor. SO_2 was also released to the atmosphere from less efficient mine operations. These releases may increase sulfate and acid concentrations in water, which in

turn enhance mercury methylation.

Climate effects on environmental signatures

In wet climates oxidation and dissolution of pyrite and marcasite increase the possibility of acid mine drainage. Formation of sulfate minerals and derivation of organic carbon from plants enhances mercury methylation by sulfate reducing bacteria in wet climates. In high temperature, dry climates, soil gas emission of elemental mercury is important; this process may increase the area affected by elevated mercury if adjacent plant communities uptake mercury in their leaves.

Geoenvironmental geophysics

Geophysical methods can be used to identify contaminated water and soil around mining operations. Electromagnetic, direct current resistivity, and induced polarization surveys can detect and monitor conductive acidic groundwater plumes resulting from oxidation and dissolution of pyrite and marcasite in altered rocks that host mercury deposits. Hot spots in tailing piles that result from ongoing redox reactions can be monitored using self potential methods. Ground penetrating radar can detect near-surface acidic water.

REFERENCES CITED

- Bailey, E.H., and Everhart, D.L., 1964, Geology and quicksilver deposits of the New Almaden District Santa Clara County, California: U.S. Geological Survey Professional Paper 360, 206 p.
- Donnelly-Nolan, J.M., Burns, M.G., Goff, F.E., Peters, E.K., and Thompson, J.M., 1993, The Geysers-Clear Lake area, California: thermal waters, mineralization, volcanism, and geothermal potential: *Economic Geology*, v. 88, p. 301-316.
- Janik, C.J., Goff, F., and Rytuba, J.J., 1994, Mercury in waters and sediments of the Wilbur Hot Springs area, Sulphur Creek Mining District, California: *EOS Transactions American Geophysical Union*, v. 75, no. 44, p. 243.
- Hurley, J.P., Krabbenhoft, D.P., Babiarz, C.L., and Andren, A.W., 1994, Cycling of mercury across the sediment-water interface in seepage lakes, *in* Baker, A., ed.: *American Chemical Society Series No. 237, Environmental chemistry of lakes and reservoirs*, p. 425-449
- Lindberg, S.E., Meyers, T.P., Taylor, G.E., Turner, R.R., and Schroeder, W.H., 1992, Atmosphere-surface exchange of mercury in a forest: results of modeling and gradient approaches: *Journal of Geophysical Research*, v. 97, no. D2, p. 2519-2528.
- Nriagu, J.O., and Pacyna, J.M., 1988. Quantitative assessment of worldwide contamination of air, water and soils by trace metals: *Nature*, v. 333, p. 134-139.
- Peabody, C.E., and Einaudi, M.T., 1992, Origin of petroleum and mercury in the Culver-Bear Cinnabar deposit, Mayacmas district, California: *Economic Geology*, v. 87, p. 1078-1102.
- Rytuba, J.J., 1986, Descriptive model of silica-carbonate Hg, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models*: U.S. Geological Survey Bulletin 1693, p. 181.
- _____, 1995, Cenozoic metallogeny of California: *Geological Society of Nevada Symposium on Geology and Ore Deposits of the American Cordillera, Program and Abstracts*, p. A68.
- Rytuba, J.J., and Miller, W.R., 1994, Environmental geochemistry of active and extinct hot spring mercury deposits in the California Coast Ranges, *in* USGS Research on Mineral Resources-1994 Part A-Program and Abstracts: U.S. Geological Survey Circular 1103-A, p. 90-91.
- Sherlock, R.L., Logan, M.A.V., and Jowett, E.C., 1993, Silica carbonate alteration of serpentinite, implications for the association of precious metal and mercury mineralization in the Coast Ranges, *in* Rytuba, J.J., ed., *Active geothermal systems and gold-mercury deposits in the Sonoma-Clear Lake volcanic fields*: *Society of Economic Geology Guidebook 16*, p. 90-116.
- Varekamp, J.C., and Buseck, P.R., 1986, Global mercury flux from volcanic and geothermal sources: *Applied Geochemistry*, v. 1, p. 65-73.
- Yates, R.G., and Hilpert, L.S., 1946, Quicksilver deposits of the eastern Mayacmas District, Lake and Napa Counties, California: *California Journal of Mines and Geology*, v. 42, no. 3, p. 231-286.

STIBNITE-QUARTZ DEPOSITS (MODELS 27d,e and 36c; Bliss and Orris, 1986a-c; Berger, 1993)

by Robert R. Seal, II, James D. Bliss, and David L. Campbell

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposits described in this model are designated "Stibnite-quartz deposits" to describe a group of antimony deposits that share many of the characteristics of simple (vein dominated) antimony deposits (Model 27d; Bliss and Orris, 1986a,b), disseminated antimony deposits (Model 27e; Bliss and Orris, 1986c), and gold-antimony deposits (Model 36c; Berger, 1993), but have features that distinguish them from these models. The Lake George deposit (New Brunswick, Canada) is included in the "stibnite-quartz deposit" geoenvironmental model. However, it was also included by Bliss and Orris (1986a) in their simple antimony (27d) and disseminated antimony (27e) models. The most significant distinction between stibnite-quartz deposits and simple antimony and disseminated antimony models is the lack of an association with volcanic rocks and a minimal association with intrusive rocks. Stibnite-quartz deposits are hosted dominantly by shale, marl, and carbonate rocks (\pm quartzite and granite) or their low-grade metamorphic (greenschist facies) equivalents, whereas many gold-antimony deposits are associated with mafic and ultramafic metavolcanic rocks. Stibnite-quartz deposits are most similar to those gold-antimony deposits that are hosted by Late Proterozoic turbiditic black shale, siltstone, sandstone, and carbonate rocks; however, gold grades of the stibnite-quartz deposits are distinctly lower than those of the gold-antimony deposits. Gold has been identified in the Lake George (New Brunswick, Canada) stibnite-quartz deposit, but it is present in a minor vein set (Seal and others, 1988) and has not been extracted during mining and milling of the ore. Relative to simple, disseminated, and gold-antimony deposits, stibnite-quartz deposits lack significant copper, lead, zinc, and nickel sulfide and sulfosalt minerals. The stibnite-quartz deposits are broadly analogous to the "Quartz-Stibnite Association" of Gumiel and Arribas (1987) in Spain and Portugal.

Deposit geology

Stibnite-quartz deposits are hosted by shale, calcareous shale, limestone, quartzite, or granite (or their metamorphic equivalents). Mineralized rock, which is associated with faults that transect stratigraphy, consists of (1) massive veins (as much as 4 m thick), dominated by quartz and stibnite; or (2) massive stratiform replacement deposits of quartz and stibnite along shale/limestone contacts. Significant metallic zonation generally is absent from these deposits.

Examples

Lake George, New Brunswick, Canada; Thompson Falls, Mont.; Xiguanshan, China; Kadamdzhay, Russia

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and others, 1986) include stibnite-bearing veins, pods, and disseminations containing base metal sulfide minerals \pm cinnabar \pm tungsten (Models 27d and 27e); gold-antimony deposits (Model 36c); low-sulfide gold-quartz veins (Model 36a); stockwork tungsten-molybdenum deposits; and less commonly, polymetallic veins (Model 22c) and tungsten skarns (Model 14a).

Potential environmental considerations

- (1) The acid-generating potential of stibnite-quartz deposits is low due to the abundance of stibnite and low abundances of pyrite and pyrrhotite. However, rock surrounding the veins includes alteration zones that contain minor pyrite and arsenopyrite, which slightly increase associated acid-generating potential. Shale that hosts the vein deposits lacks significant acid-buffering capacity. However, low acid-buffering capacity may be offset by the local presence of calcite gangue. Limestone that hosts replacement deposits has significant acid-buffering capacity.
- (2) Mine drainage and water from tailings ponds may contain elevated metal abundances, including tens to thousands of mg/l antimony, tens to hundreds of mg/l arsenic, and tens to thousands of mg/l sulfate.

Exploration geophysics

No geophysical investigations specific to this model are known. Induced polarization methods can provide qualitative estimates of sulfide mineral percentages and grain size.

References

Geology: Morrissy and Ruitenberg (1980), Smirnov and others (1983), Seal and others (1988), and Panov and No

(1989).

Environmental geology, geochemistry: Shvartseva (1972) and Woessner and Shapley (1984).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Most deposits are of small to intermediate size, <0.1 to 2.0 million tonnes.

Host rocks

Stibnite-quartz deposits are hosted by shale (Lake George, Thompson Falls), marl (Lake George), limestone (Kadamzhay, Xiguanshan) or granite (Lake George), or low-grade (greenschist) metamorphic equivalents.

Surrounding geologic terrane

Stibnite-quartz deposits are primarily in sedimentary or metasedimentary ± granitic terranes.

Wall-rock alteration

Wall rock for vein deposits (Lake George, Thompson Falls) is altered to sericitic and siliceous assemblages. Rock altered to sericitic assemblages, which surrounds veins out to distances of tens of meters, is dominated by quartz and sericite, with minor pyrite and arsenopyrite, whereas that altered to siliceous assemblages is dominated by quartz with lesser pyrite, arsenopyrite, and stibnite and extends only several centimeters into wall rock. Replacement deposits (Kadamzhay, Xiguanshan) are typified by silicification that extends tens of meters into the host limestone.

Nature of ore

Vein deposits are overwhelmingly dominated by veins of quartz cored by massive stibnite. Most replacement deposits form lenticular bodies of quartz and stibnite within limestone, at contacts with overlying shale, near high-angle faults.

Deposit trace element geochemistry

Main ore zones contain elevated abundances of $Sb > Fe > As \pm Pb \pm Zn \pm Cu \pm U \pm Ba$. Lead, zinc, copper, uranium, and barium are present as minor constituents of ore minerals in local zones in some deposits. Sericitic alteration assemblages contain elevated abundances of iron and arsenic.

Ore and gangue mineralogy and zonation

Minerals listed in decreasing order of abundance. Potentially acid-generating minerals underlined. Quartz, stibnite, pyrite, calcite, native antimony, arsenopyrite, pyrrhotite, berthierite, sphalerite, tetrahedrite, lead sulfosalts, barite, fluorite, chalcopyrite, hematite. Veins are typically zoned from outer quartz-dominated margins to stibnite-dominated cores. At Lake George, high sulfidation assemblages (stibnite + pyrite) in the eastern part of the vein are laterally zoned to low sulfidation assemblages (native antimony + pyrrhotite) in its western part.

Mineral characteristics

Stibnite grains range from less than 1 mm to as much as approximately 50 cm long. Grain habits range from anhedral to euhedral. Sheared and kink-banded fabrics are common. Vug fillings locally are present within the deposits. Accessory sulfide minerals are typically less than 1 mm in diameter.

Secondary mineralogy

Minerals formed by supergene oxidation include: valentinite (orthorhombic Sb_2O_3), senarmontite (cubic Sb_2O_3), cervantite (Sb_2O_4), kermesite (Sb_2S_2O), and stibioconite ($(Ca,Sb)_2Sb_2O_6(O,OH)$), and limonite. None of these minerals are readily soluble.

Topography, physiography

Topography and physiography vary widely and cannot be generalized.

Hydrology

Rock cut by vein-filled or replacement-deposit-related faults may have enhanced permeability. Otherwise, local hydrology is not significantly influenced by features associated with these deposits.

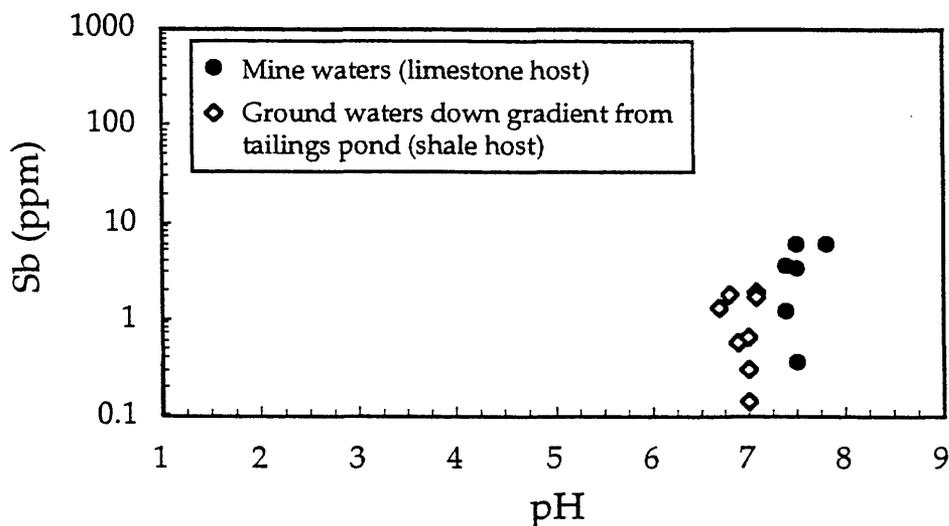


Figure 1. Plot of pH versus dissolved antimony in mine and ground water down gradient from a tailings pond. Data from Shvartseva (1972) and Woessner and Shapley (1984).

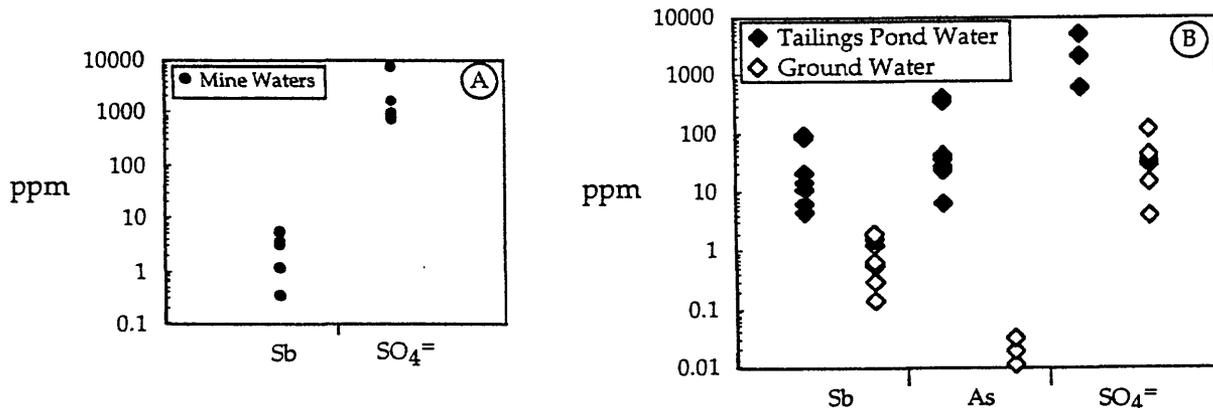


Figure 2. Plot of antimony, arsenic, and sulfate concentration ranges associated with stibnite-quartz deposits. A, mine water data, Kadamzhay deposit, Russia (Shvartseva, 1972); B, tailings pond and ground water data (within 50 m, down gradient, of tailings pond), Thompson Falls deposit, Mont. (Woessner and Shapley, 1984).

Mining and milling methods

These deposits have been exploited by a combination of underground and surface mining techniques. Ore is roasted or smelted to produce antimony metal or antimony trioxide (Sb_2O_3).

ENVIRONMENTAL SIGNATURES

Drainage signatures

Mine water draining limestone-hosted replacement ore (Kadamzhay, Russia) is neutral (pH 7.4 to 7.8) and contains elevated dissolved metal abundances, including 0.4 to 5.7 mg/l antimony and 750 to 7637 mg/l sulfate (figs. 1 and 2). Stream water within 3 km of the deposit is also neutral (pH 7.0 to 7.1) and contains elevated dissolved metal abundances, including 0.06 to 0.24 mg/l antimony and 50 to 90 mg/l sulfate (Shvartseva, 1972). No data are available for shale-hosted vein deposits.

Metal mobility from solid mine wastes

Water from the tailings pond of shale-hosted vein ore waste (Thompson Falls, Mont.) has elevated dissolved metal concentrations, including 6 to 100 mg/l antimony, 6 to 380 mg/l arsenic, 0.05 to 3.4 mg/l cadmium, copper, iron, manganese, and zinc, and 570 to 4,800 mg/l sulfate (Woessner and Shapley, 1984); pH data for tailings-pond water

are not available. Down-gradient ground water within 50 m of the tailings pond for shale-hosted vein ore waste is near neutral (pH 6.7 to 7.1) and contains elevated metal concentrations, including 0.14 to 1.9 mg/l antimony, 12 to 33 µg/l arsenic, and 4 to 125 mg/l sulfate (figs. 1 and 2).

Soil, sediment signatures prior to mining

Above the surface projection of mineralized veins in the vicinity of the Lake George (New Brunswick, Canada) deposit, soil samples (B horizon) contain a maximum of 565 ppm antimony. Background values are less than 2 ppm (Austria, 1971). Regional stream sediment data for the Lake George area indicate a general correlation between antimony and arsenic contents; maximum antimony abundances are 900 ppm, whereas maximum arsenic abundances are 170 ppm (Austria, 1971; Pronk, 1992). Antimony and arsenic concentrations are less than 20 ppm in stream sediment from sites upstream from the known extent of mineralized rock and from drainages in areas not known to contain mineralized rock.

Potential environmental concerns associated with mineral processing

Water associated with tailings ponds may contain high abundances of antimony, arsenic, and sulfate.

Smelter signatures

No data.

Climate effects on environmental signatures

No generalizations can be made concerning the relationship between climate and environmental signatures because of the limited amount of environmental data available for this deposit type. However, in most cases the intensity of environmental impact associated with sulfide-mineral-bearing mineral deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell.

Geoenvironmental geophysics

Metal-bearing ground water plumes may be traceable using geoelectric methods, including the ground slingram. Plumes associated with stibnite-quartz deposits may contain elevated sulfate ion contents which renders them electrically conductive. Slingrams such as the Geonics EM-31 or EM-34 give readings of greater than about 25 mS/m within about 5 m of metal-charged plumes. In ideal circumstances, contaminant plumes can be rapidly outlined by sequential traverses across their edges.

Comments

The stibnite-quartz geoenvironmental model is probably generally applicable to ore deposit models 27d, 27e, and 36c. The acid-buffering capacity of igneous rocks associated with some of these deposits is probably not significantly different from that of shale-hosted stibnite-quartz deposits. Key differences between stibnite-quartz veins and those of models 27d, 27e, and 36c that may significantly affect associated environmental impact include: (1) the presence of minor cinnabar in the latter, (2) the presence of siderite in deposits of the Model 36c type, and (3) specific mineral-processing and mining techniques applied to each of the different deposit types.

REFERENCES CITED

- Austria, V.B., Jr., 1971, The Cu, Pb, Zn, Mn, Mo, and Sb content of stream and spring sediments, York County, New Brunswick: New Brunswick Department of Natural Resources, Mineral Resources Branch Report of Investigation, No. 14, 18 p.
- Berger, V.I., 1993, Descriptive and grade and tonnage model for gold-antimony deposits: U.S. Geological Survey Open-File Report 93-194, 24 p.
- Bliss, J.D., and Orris, G.J., 1986a, Descriptive model of simple Sb deposits, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 183.

- _____ 1986b, Grade and tonnage model of simple Sb deposits, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 184-186.
- _____ 1986c, Grade and tonnage model of disseminated Sb deposits, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 187-188.
- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- Gumiel, P., and Arribas, A., 1987, Antimony deposits in the Iberian Peninsula: *Economic Geology*, v. 82, p. 1453-1463.
- Morrissy, C.J., and Ruitenberg, A.A., 1980, Geology of the Lake George antimony deposit, southern New Brunswick: *Canadian Institute of Mining and Metallurgy Bulletin*, v. 73, p. 79-84.
- Panov, B.S., and No, L., 1989, The Xiguanshan antimony deposit, China: *International Geology Review*, v. 31, p. 100-110.
- Pronk, A.G., 1992, The use of regional stream sediment data in assessing drinking water quality; an example from Southwest New Brunswick: *Atlantic Geology*, v. 28, p. 208.
- Seal, R.R., II, Clark, A.H., and Morrissy, C.J., 1988, Lake George, southwestern New Brunswick: a Silurian, multi-stage, polymetallic (Sb-W-Mo-Au-base metal) hydrothermal centre: *Canadian Institute of Mining and Metallurgy Special Volume 39*, p. 252-264.
- Shvartseva, N.M., 1972, Antimony in ground water of the Kadamzhay Deposit: *Academy Science USSR, Dokl., Earth Science Section*, v. 207, p. 224-226.
- Smirnov, V.I., Ginzburg, A.I., Grigoriev, V.M., and Yakovlev, G.F., 1983, *Studies of mineral deposits*: Moscow, Mir, 288 p.
- Woessner, W.W., and Shapley, M., 1984, The effects of U.S. antimony's disposal ponds on an alluvial aquifer and Prospect Creek, western Montana: *Montana University Joint Water Resources Research Center Completion Report G-853-03*, 81 p.

ALGOMA FE DEPOSITS (MODEL 28b; Cannon, 1986)

by William F. Cannon, Donald G. Hadley, and Robert J. Horton

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Algoma type iron-formation is interbedded with submarine mafic to felsic volcanic rocks and volcanoclastic graywacke and shale; most deposits are in Archean greenstone belts, but some are in younger rocks of similar character. Most Algoma type iron-formation formed in island arc and related suites and was subsequently strongly deformed in orogenic belts. Most ore is oxide facies rock that consists of interlayered magnetite or hematite and metachert; less commonly iron-carbonate facies rocks are mined. No deposits of this type are currently being mined in the United States.

Examples

Archean examples: Vermillion Iron-Formation, Minn.; Sherman Mine, Temagami, Ontario; Helen Mine, Wawa, Ontario; Early Proterozoic example: Wadi Sawawin, Saudi Arabia.

Spatially and (or) genetically related deposit types

Some Algoma type iron-formation grades laterally into polymetallic sulfide facies.

Potential environmental considerations

(1) Processing ore to concentrate iron minerals produces large volumes of fine-grained tailings that must be permanently stored. Potential concerns related to voluminous tailings include: (a) silica-rich dust, (b) fibrous silicate minerals in air and water, (c) particulate and colloidal iron compounds in discharge water, (d) mixing tailings impoundment water with ground water, (e) long-term stability of tailings impoundments, and (f) mineral dust in stack emissions from kilns.

Ore that contains amphibole minerals is of particular concern because it has the potential to generate fine-grained acicular cleavage fragments that meet some legal definitions of asbestos; natural amphibole asbestos poses similar concerns. Crocidolite, the fibrous variety of riebeckite, and amosite, the fibrous variety of grunerite-cummingtonite amphibole, are known carcinogens of both the lungs and the digestive tract and can be harmful even with less than occupational exposure. Both minerals are present in some iron-formation but are far from ubiquitous. The non-asbestiform variety of grunerite-cummingtonite amphibole is common in iron-formation, including much that is mined and processed. Fine acicular particles, legally classed as asbestos, produced by fine-grinding are potentially harmful. However, epidemiological studies of miners and mill workers at a taconite mine in Minnesota, where ore contains abundant cummingtonite-grunerite, found no evidence of excess cancer (Ross, 1984). Nevertheless, any iron-formation containing amphibole probably requires special consideration with regard to mine design, milling, and waste disposal practices to minimize discharge of amphibole particles into the environment. All of these hazards are successfully mitigated at numerous large mining and processing operations.

(2) Waste rock and tailings may contain sulfide minerals associated with deposits in which iron-formation and sulfide-mineral-bearing facies are in close spatial association. These situations have some potential for acid generation, but this potential hazard is not universal.

(3) Deposits are mined from open pits, which result in a relatively large, and partly permanent surface disturbance.

(4) Ore from carbonate facies deposits may be sintered to produce iron-oxide concentrates. Stack emissions produced when carbonate ore is processed may include sulfur or other trace components.

Exploration geophysics

Gravity and magnetic methods can be used to delineate greenstone belts within granite-greenstone terranes at provincial to regional scales. Magnetic low and gravity high anomalies are usually associated with relatively nonmagnetic, dense greenstone terranes, whereas magnetic high and gravity low anomalies are usually associated with magnetic, low-density granitic terranes (Innes, 1960; Bhattacharya and Morely, 1965; McGrath and Hall, 1969; Tanner, 1969; and Condie, 1981). Gravity and magnetic methods can also be used for deposit-scale iron-formation studies. Most iron-formation is associated with positive, high-amplitude gravity anomalies because it contains elevated abundances of high-density iron minerals, including magnetite and hematite. The magnetic signature of

iron-formation is usually one to two orders of magnitude greater than that of its host rock (Bath, 1962; Sims, 1972). Remote sensing imaging spectroscopy can also be used in regional exploration (Hook, 1990) because iron ore minerals and their alteration products have distinct spectral signatures (Clark and others, 1993).

The magnetic character of iron-formation is dependent on magnetic mineral content, alteration, structural attitude, and remanent magnetization. Iron-formation with low magnetite content, or deposits in which magnetite has been oxidized to non-magnetic hematite, produce low-amplitude anomalies of tens to hundreds of nanoTeslas. Flat-lying deposits with normal magnetic polarization typically produce positive anomalies of about several thousand nanoTesla. Steeply dipping or folded iron-formation dominated by remanent magnetic polarization can produce anomalies with extremely high positive amplitudes of as much as tens of thousands of nanoTesla.

Electrical and electromagnetic methods are generally not applied to iron-formation exploration because the ore is resistive owing to high silica (chert) content. However, electrical techniques could be used to locate conductive sulfide facies or to delineate graphitic shale horizons associated with ore deposits.

References

Geology: Goodwin (1973), Gross (1973, 1980, 1988), and Davies and Grainger (1985).
Environment: Ross (1984), Gross (1988), and Myette (1991).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Deposits are small (a few million tonnes) to very large (billions of tonnes); median deposit size is 170 million tonnes (Mosier and Singer, 1986).

Host rocks

Host rocks include a variety of volcanic and volcanoclastic rocks including basalt, andesite, dacite, rhyolite, graywacke, shale, and graphitic shale.

Surrounding geologic terrane

The geologic terrane surrounding Algoma iron deposits usually consists of strongly deformed and variably metamorphosed submarine volcanic sequences.

Wall-rock alteration

No wall rock alteration is associated with Algoma iron deposits. Although deposits are believed to be related genetically to submarine hydrothermal vents, nearly all known deposits are distal to vents and have no obvious related alteration.

Nature of ore

Most ore is banded rock in which iron-rich and chert bands are interlayered on a scale of one to a few centimeters. Several depositional facies are common and may be in stratigraphic superposition or as lateral equivalents. Oxide facies ore consists of both magnetite and hematite ore, and is economically the most important; iron carbonate ore is less commonly mined. Sulfide facies ore is present widely but is seldom mined. Ore grade is relatively uniform, typically about 30 to 35 weight percent iron, but may vary from 15 to 45 weight percent. Grain size varies according to degree of metamorphism as does the nature of gangue minerals. A critical factor for environmental consideration is the metamorphic development of iron-amphibole, which may generate fibrous particles during processing. Iron amphibole commonly is present in middle greenschist facies or higher metamorphic grade rocks.

Deposit trace element geochemistry

Analyses of major and trace element abundances in about 1,000 Algoma-type iron-formation samples from the Canadian shield, representing most known deposits, were summarized by Gross (1988). All determined trace element abundances are low, generally at or below average crustal abundance. One exception is gold, whose average abundance is about an order of magnitude above average crustal abundance, but still in the 0.0X to 0.00X ppm range. Except for sulfide facies iron-formation, very rarely exploited as iron ore, potential environmental effects related to trace element abundances are minimal. Sulfide facies rocks included in some mine waste, pose limited potential for acid drainage generation or release of heavy metals.

Ore and gangue mineralogy and zonation

Ore minerals are predominantly magnetite and hematite, less commonly siderite. Gangue is mostly quartz in the form of variably metamorphosed chert beds. Other gangue minerals that might be present, depending on original facies of deposition and degree of metamorphism, include greenalite, minnesotaite, stilpnomelane, iron-amphibole, iron-pyroxene, garnet, and pyrite, generally present in only trace amounts. Magnetically concentrated ore may include hematite and iron carbonate minerals as gangue.

Mineral characteristics

The most important mineral characteristic is the presence or absence of amphibole that might contribute natural asbestos fibers or asbestos-like grains produced during processing. Amphibole is a common metamorphic mineral in iron-formation and may be present in middle greenschist facies or higher metamorphic grade rocks. Original grain size is also important and varies as a function of metamorphic grade. Weakly metamorphosed iron-formation is extremely fine-grained and requires very fine grinding (as fine as 0.03 mm in some cases) to liberate iron minerals from gangue. More highly metamorphosed ore is coarser-grained and requires less grinding. The maximum grain size after grinding is generally about 0.1 mm, even for the most coarse-grained ore. Grain size fineness is correlated with increased potential for problems with dust from tailings basins, colloidal and particulate suspensions of ore and gangue minerals in released process water, and higher tailings weathering rates.

Secondary mineralogy

Because tailings are generally very-fine grained, weathering and formation of secondary minerals may proceed quickly. Iron oxide minerals alter to iron hydroxide minerals. Iron silicate minerals alter to iron hydroxide minerals and clay. Most alteration minerals are highly insoluble. Sulfide minerals, mainly pyrite, may also quickly alter and generate small amounts of acid. Much ore also contains at least trace amounts of carbonate minerals, which, when present, are probably adequate to neutralize any acid generated.

Topography, physiography

Algoma-type iron-formation deposits are found in a variety of physiographic settings. They are characteristic deposits of Archean shields; many are in areas of low relief. They may also be present in high relief areas, particularly where older shields have been incorporated in younger orogenic belts. The principal topographic and physiographic concern associated with Algoma-type iron-formation deposits relates to large volumes of tailings that are characteristically produced. In areas of high relief, it may be difficult to site tailings impoundments with adequate volume. In settings where rapid surface water runoff can produce flash flood hazards, impoundments must be protected from failure.

Hydrology

Hydrologic communication between ground water, waste piles, and tailings is a predictable consequence of mining. A detailed study of a taconite tailings basin in Minnesota and its surroundings (Myette, 1991) suggests that associated environmental problems are minimal. Abundances of components dissolved in water of a tailings test well are well below maximum abundances permitted by state standards for drinking water, except those of fluoride, which are near the maximum permitted abundance. Particulate abundances in discharge water are also low, except during occasional periods of very high precipitation or snow melt.

Mining and milling methods

With few exceptions, Algoma-type iron-formation is mined in open pits, and ore is processed to high-grade concentrates and pelletized at mine sites. Open pit mining tends to produce relatively large volumes of waste rock that must be disposed of near mines. Mine waste generally includes a variety of volcanic and volcanoclastic rocks with which iron-formation is interlayered. Ore concentration generates large volumes of tailings, mostly composed of silica and lesser iron silicate and iron carbonate minerals. Where iron carbonate is the ore mineral, mine sites may also include roasting or sintering plants; stack emissions, particularly if the ore contains sulfide minerals, may contain elevated metal abundances that may accumulate in downwind areas. Stack emissions of mineral dust might also be a concern; scrubbing or filtering might be required to eliminate dust problems.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Pre-mining drainage signatures for Algoma-type iron-formation deposits are unknown. In virtually all weathering regimes, primary iron minerals break down to iron hydroxide minerals and clay that are highly insoluble. With intense weathering, silica is lost, but not in concentrations that produce a detectable geochemical signature. Some asbestos-like particles may be released into surface water; however, the U.S. Environmental Protection Agency has concluded that ingestion of asbestos fibers poses no significant cancer risk (U.S. Environmental Protection Agency, 1991).

Metal mobility from solid mine wastes

Except in special cases, in which sulfide-mineral-rich rocks might be included in waste rock, metal mobility is probably negligible. Carbonate minerals in mine waste may mitigate acid generated by oxidation of sulfide minerals in sulfide-mineral rich waste. Iron weathers to largely insoluble compounds and the abundances of other metals in iron-formation are at or below average crustal abundances.

Soil, sediment signatures prior to mining

Pre-mining soil and sediment signatures for Algoma-type iron-formation deposits are unknown but stream sediments probably contain high iron abundances. In areas of intense weathering, iron-rich laterite, some of which is itself iron ore, may develop on iron-formation. In glaciated areas, most iron formation is virtually unweathered and has no associated characteristic soil signature.

Potential environmental concerns associated with mineral processing

Most Algoma-type iron-formation ore is ground to 0.1 mm or finer, concentrated by magnetic or specific gravity techniques, and formed into pellets, which are then fire hardened in rotary kilns, at or near mine sites. The large volume of tailings generated are stored in nearby impoundments. The principal environmental concern involves continued physical isolation of tailings, particularly fine-grained silica and fibrous silicate minerals. Redistribution by wind can be mitigated by wetting and vegetating abandoned tailings areas. Redistribution in surface water can be minimized at active mines by reuse of tailings water so that outflow is restricted to periods of very high precipitation. The long term, post-mining stability of tailings impoundments must be assured in their design.

Combustion products from rotary kilns are generally vented through stacks and may carry fine ore particles that should be removed by scrubbing or filtering before combustion products are released to the atmosphere. On-site sintering mills used to process carbonate facies ore may require assurance of acceptable stack emissions.

Smelter signatures

No smelting is involved in production of Algoma-type iron ore.

Climate effects on environmental signatures

Principal climatic concerns relate to the continued integrity of tailings impoundments in climates with high annual or seasonal precipitation and with airborne redistribution of tailings in dry climates. Even in humid climates, milling operations generally reuse nearly all process water to minimize water outflow through tailings basins. In climates susceptible to extreme precipitation, however, measures are required to assure that flooding does not compromise the containment of tailings either during or after mining.

Geoenvironmental geophysics

Electrical methods can be used to identify conductive ground water plumes produced by high abundances of dissolved solids, colloids, and acid. The self potential method can detect leaks in tailings impoundment dikes. Remote sensing methods can be used to quantify areas of permanent surface disturbance related to mining and ore processing. Remote sensing methods may also be used to identify areas of stressed vegetation related to sulfur and fugitive-metal stack emissions and contaminated surface water.

REFERENCES CITED

Bath, G.D., 1962, Magnetic anomalies and magnetization of the Biwabik iron-formation, Mesabi area, Minnesota: Geophysics, vol. 27, p. 627-650.

- Bhattacharya, B.K., and Morley, L.W., 1965, The delineation of deep crustal magnetic bodies from total field aeromagnetic anomalies: *Journal of Geomagnetism and Geoelectronics*, v. 17, p. 237-252.
- Cannon, W.F., 1986, Descriptive model of Algoma Fe, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 198.
- Clark, R.N., Swayze, G.A., and Gallagher, A., 1993, Mapping minerals with imaging spectroscopy, *in* Scott, R.W., Jr., and others, eds., *Advances related to United States and international mineral resources--Developing frameworks and exploration techniques: U.S. Geological Survey Bulletin 2039*, p. 141-150.
- Condie, K.C., 1981, *Archean greenstone belts: Elsevier Scientific Publishing Company*, 434 p.
- Davies, F.B., and Grainger, D.J., 1985, Geologic map of the al Muwaylih quadrangle, sheet 27A, Kingdom of Saudi Arabia: Deputy Ministry of Mineral Resources Geologic Map GM-82A, 32 p.
- Goodwin, A.M., 1973, Archean iron-formations and tectonic basins of the Canadian Shield: *Economic Geology*, v. 68, p. 915-933.
- Gross, G.A., 1973, The depositional environment and principal types of Precambrian iron-formation, *in* *Genesis of Precambrian iron and manganese deposits, Proceedings of the Kiev Symposium, 1970: UNESCO Earth Sciences 9*, p. 15-21.
- _____, 1980, A classification of iron-formations based on depositional environments: *Canadian Mineralogist*, v. 18, p. 215-222.
- _____, 1988, Gold content and geochemistry of iron-formation in Canada: *Geological Survey of Canada Paper 86-19*, 54 p.
- Hook, S.J., 1990, The combined use of multispectral remotely sensed data from the short wave infrared (SWIR) and thermal infrared (TIR) for lithological mapping and mineral exploration: *Fifth Australasian Remote Sensing Conference, Proceedings, Oct., 1990*, v. 1, p. 371-380.
- Innes, M.J.S., 1960, Gravity and isostasy in northern Ontario and Manitoba: *Dominion Observatory of Ottawa Publication*, v. 21, p. 261-338.
- McGrath, P.H., and Hall, D.H., 1969, Crustal structure in northwestern Ontario: *Regional aeromagnetic anomalies: Canadian Journal of Earth Science*, v. 6, p. 191-207.
- Mosier, D.L., and Singer, 1986, Grade and tonnage model of Superior Fe and Algoma Fe deposits, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 228-230.
- Myette, C.F., 1991, Hydrology, water quality, and simulation of ground-water flow at a taconite-tailings basin near Keewatin, Minnesota: *U.S. Geological Survey Water-Resources Investigations Report 88-4230*, 61 p.
- Ross, M., 1984, A survey of asbestos-related disease in trades and mining occupations and in factory and mining communities as a means of predicting health risks of nonoccupational exposure to fibrous minerals: *American Society for Testing and Materials Special Technical Publication 834*, p. 51-104.
- Sims, P.K., 1972, Magnetic data and regional magnetic patterns, *in* Sims, P.K., and Morey, G.B., eds., *Geology of Minnesota, Minnesota Geological Survey*, p. 585-592.
- Tanner, J.G., 1969, A geophysical interpretation of structural boundaries in the Eastern Canadian Shield: Durham, England, University of Durham, Ph.D. Dissertation.
- U.S. Environmental Protection Agency, 1991, Final national primary drinking water rules: *56 Federal Register 3578 (Jan. 30, 1991)*.

SEDIMENT-HOSTED CU DEPOSITS (MODEL 30b; Cox, 1986)

by David A. Lindsey, Laurel G. Woodruff, William F. Cannon,
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SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

The sediment-hosted copper model (Cox, 1986, Model 30b) has been subdivided into three models having different geologic features, grades and tonnages, and anticipated environmental effects associated with mining and processing. The reduced-facies model (RF) includes deposits in widespread reduced-facies sedimentary rocks, is relatively high-tonnage, and has been mined mostly underground. The only major, reduced facies deposit mined in the United States, White Pine, Mich., produced 138 million tonnes of ore that contained 1.14 weight percent copper and 8 g/t silver between 1953 and 1982 (Kirkham, 1989). The redbed model (RB) includes deposits in local areas of reduced rocks in redbed sequences, is low-tonnage, and has been mined near the surface by open-pit and small underground mines. Redbed deposits have not been a major source of copper. The Revett model (RV; Spanski, 1992), based on deposits restricted to the Proterozoic Revett Formation of the Belt Supergroup of Montana and Idaho, is intermediate in tonnage and has been mined entirely underground. The now-closed Spar Lake, Mont., mine produced 44 million tonnes of ore that contained 0.74 weight percent copper and 53 g/t silver (Balla, 1992). Production from either one of two mines under development would exceed that of the Spar Lake mine. The silver-rich character of Revett ore makes it the largest producer of silver in the United States (E&MJ, 1982; 1989).

New geologic information and mining technology may change the classification, grade and tonnage, and environmental effects of sediment-hosted copper models in the future. Variation in geology and coproduct metals among reduced-facies deposits may require development of additional models for White Pine-, Kupferschiefer-, and Zambian-type deposits. The distinction between the Revett and redbed models may be unduly arbitrary (Lange, 1975). Sandstone-hosted deposits like those in the Revett Formation may reach gargantuan tonnages exploitable by open-pit mining (Udokan, Siberia; Volodin and others, 1994). Some deposits in Phanerozoic rocks, now included in the redbed model, may belong to the same genetic class as the Revett deposits. However, examination of environmental effects is facilitated by the present classification of all Devonian and later sandstone-hosted copper deposits in the redbed model because they share a common mineralogical association and are commonly associated with fossil plant matter. Finally, the advent of solvent extraction-electrowinning (SX-EW) mining may lead to *in situ* solution mining of underground workings in chalcocite-rich reduced facies deposits and to open-pit, heap-leach mining of previously uneconomic, near-surface oxidized and chalcocite ore in the largest redbed deposits.

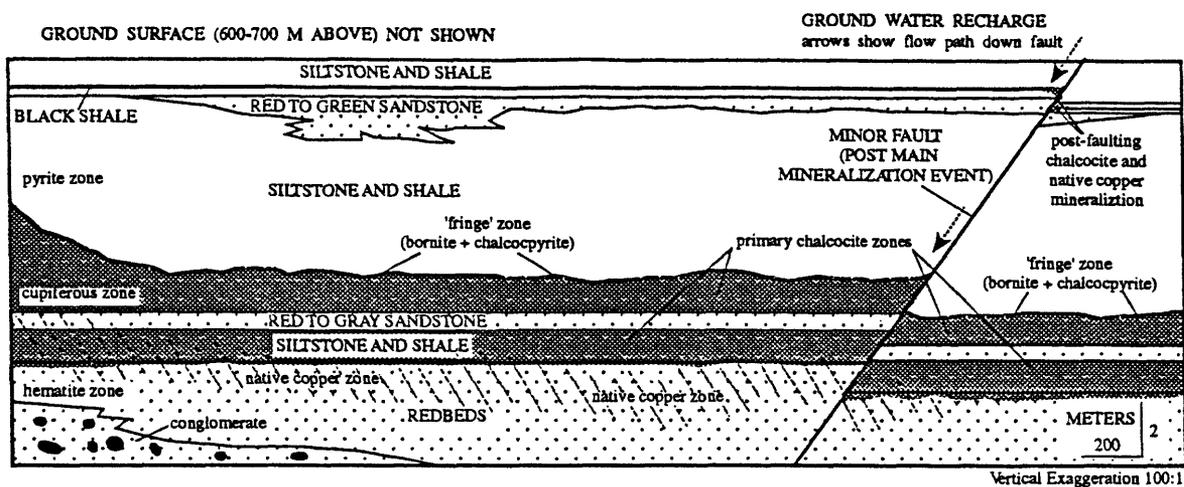
Deposit geology

Principal features of the three sediment-hosted copper models are shown diagrammatically in figure 1. These models portray dimensions, stratigraphic settings, favorable host rocks, mineral zones, degree of oxidation, fractures, ground water flow, and mining methods of known deposits. Ore fluids were warm (50 to 150°C), oxidizing (hematite-buffered), and rich in sulfate and chloride ions (to complex Cu⁺) (Jowett, 1986; Hayes, 1990).

RF: Deposits of the reduced-facies model are present where continental clastic sedimentary rocks are overlain by regionally extensive marine or lacustrine shale or carbonate rocks, rich in organic material, that act as traps for mineral deposition (Ensign and others, 1968; Oszczepalski, 1989). Host rocks may be shale or adjacent limestone, sandstone, or conglomerate. Commonly, the reduced facies overlies basaltic volcanic rocks in rift environments. Where evidence for a rift is lacking, reduced facies overlie coarse clastic sedimentary rocks derived from older terranes that contain mafic rocks. Evaporite deposits overlie, or are believed to have once overlain, copper deposits of the reduced-facies model.

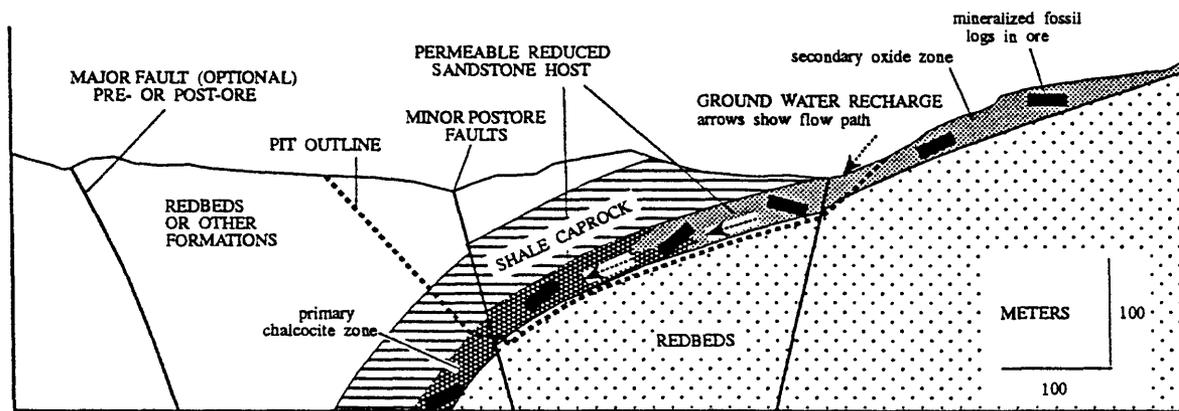
RB: Deposits of the redbed model are in the same geologic setting as those of the reduced-facies model but lack regionally extensive reduced strata. In Devonian and later strata, copper commonly replaces local accumulations of fossil plant matter (LaPoint, 1976). Redbed copper deposits may be present in rifts or intracratonic basins.

RV: Deposits of the Revett model are in thick beds of reduced (pyritic) quartzite (properly, metasandstone) near pre-ore redox fronts (Hayes and Einaudi, 1986; Hayes, 1990). Orebodies may be stacked, especially near faults (Balla, 1993). Copper is not associated with solid organic matter in Revett deposits, but copper may have been deposited by a transient gas reductant generated by decay of organic matter.



REDUCED FACIES MODEL
 (White Pine-type, modified from Mauk and others, 1992;
 variations include no faults, no post-fault mineralization,
 presence of carbonates and evaporites [Kupferschiefer-type])

A

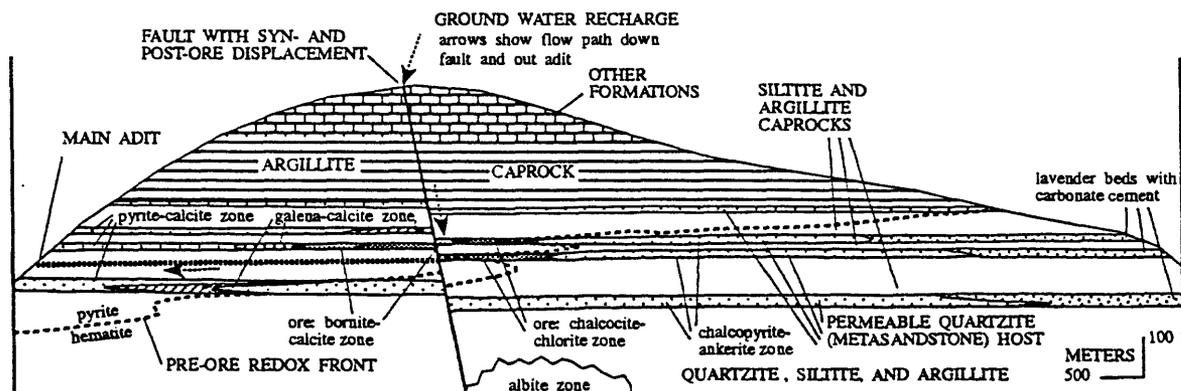


Supergene Mineral Zones Shown

No Vertical Exaggeration

REDBED COPPER MODEL
 (modified from Talbot, 1974; Woodward and others, 1974;
 variations include no faults, flat-lying beds, stacked ore bodies, few mineralized logs)

B



Hypogene Mineral Zones Shown

Vertical Exaggeration 5:1

REVETT COPPER MODEL
 (modified from Hayes, 1990, and Hayes and Einaudi, 1986;
 variations include number and placement of stacked ore bodies and location of faults)

C

Figure 1. Simplified cross-sections of sediment-hosted copper deposits: A, reduced facies, B, redbed, and C, Revett models. Note scale variations and vertical exaggeration.

Examples

RF: White Pine, Mich.; Creta, Okla.; Kupferschiefer, Germany and Poland; and African copperbelt, Zaire and Zambia.

RB: Nacimiento, Scholle, and Stauber, N. Mex.; and Paoli, Okla.

RV: Spar Lake, Rock Creek, and Montanore, Mont.

Spatially and (or) genetically related deposit types

The three sediment-hosted deposit types are genetically related and may be present in the same terrane. Hypothetically, all three deposit types might form from a single ore-forming fluid that invaded reduced rocks. Deposits belonging to the three models represent ore deposition in different reducing environments: laterally extensive reduced black shale and carbonate rock (reduced facies model, RF), local areas of reduced rock and plant matter in redbeds (redbed model, RB), and large reduced areas in sandstone (Revet model, RV). Where sediment-hosted copper deposits form in a rift environment, as for example in the Keweenaw peninsula, Mich., large deposits of native copper are present in vesicular basalt flows (Model 23; Cox and Singer, 1986).

Potential environmental concerns

Surface disturbance: Mines, including open pits, and mineral processing facilities occupy areas ranging from a few to many square kilometers.

Water quality: Potential for acid drainage and dissolved metals associated with these deposits is minimized by low pyrite and chalcopyrite contents and by widespread presence of carbonate minerals in ore and waste rock. Heavy metal (including arsenic, cadmium, chromium, copper, mercury, and lead) abundances downstream from mining and milling operations may be elevated; however, undesirable environmental effects have not been reported (U.S. Forest Service and others, 1992). Anomalous quantities of some elements may also be present in ground and surface water down dip or downslope from undisturbed sediment-hosted copper deposits; anomalies in ground water have been traced to small concentrations in associated rock (Mosier, in press). Lead in ore can be recovered by smelting (E&MJ, 1986a), and lead in tailings and waste rock can be minimized during mining by avoiding lead-rich zones near ore. Metals in surface water may be sorbed by particulate oxyhydroxide minerals, which can be removed by filtration through soil. Acid water may drain from tailings and waste, particularly from friable or permeable pyrite-bearing waste rock that is removed to the surface, but the presence of carbonate rock may significantly mitigate these effects. Elevated ammonia and nitrates from blasting may affect aquatic life.

Air quality: Particulate emissions from mineral processing, including smelting, may exceed air quality standards. Sulfur dioxide is a product of copper smelting, but emissions can be controlled by collection and production of sulfuric acid. Copper recovery by SX-EW instead of smelting greatly reduces impact on air quality.

Exploration geophysics

Major structural features (Unrug, 1989) and bleached redbeds (Conel and Alley, 1984) associated with uranium and copper deposits can be delineated by the Landsat Multispectral Scanner. Integrated studies of basin structure, thickness, and lithology, which may be applicable to sediment hosted copper deposits, have been conducted using electrical, electromagnetic, gravity, and seismic methods (Zohdy and others, 1974; Gomez-Trevino and Edwards, 1983; Horscroft and Nettleton, 1989; Sinha, 1990).

References

Geology General: Kirkham (1984, 1989), and Cox (1986). RF--Ensign and others (1968), Dingess (1976), Oszczepalski (1989), and Mauk and others (1992). RB--Woodward and others (1974) and LaPoint (1976). RV--Hayes and Einaudi (1986), Hayes (1990), and Balla (1993).

Environmental geology, geochemistry: RV--Balla (1992) and U.S. Forest Service and others (1992).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Size and grade of deposits vary by model (table 1). Median deposit size is related to the average size of the area potentially impacted by nearby mining; maximum deposit size indicates the size of the largest, potentially impacted area. The maximum-size reduced facies copper deposit in the United States is White Pine, Mich., which contains 560 million tonnes of 1.2 weight percent copper (Kirkham, 1989). The largest redbed copper deposit is Nacimiento, N. Mex. (Talbot, 1974). If Lisbon Valley, Utah, is included in the redbed model, maximum size is 35 million tonnes

Table 1.—Estimated median and maximum ore tonnages (reserves plus production) and copper grades of each sediment-hosted copper model type

Model	Number of deposits in model	Median size (tonnes X 10 ⁶)	Copper grade (percent)	Maximum size (tonnes x 10 ⁶)	Grade of maximum-tonnage deposit (percent)
Reduced (RF) ¹	43	32	2.3	2,600 ²	>2 ²
Redbed (RB) ¹	17	0.12	2.8	10	0.67
Revett (RV) ^{1,3}	7	19	0.86	147	0.68

¹Cox and others (1992).

²Kirkham (1989).

³Spanski (1992).

of 0.49 weight percent copper (Mining Record, 1995). If Udokan, Siberia, is included in the Revett model, maximum size is 1,200 million tonnes of 1.5 weight percent copper (Volodin and others, 1994).

Host rocks

RF: Shale, argillite, siltstone, and their calcareous variants; adjacent rocks that may be important hosts locally include limestone, dolomite, sandstone, and conglomerate.

RB: Sandstone; locally, siltstone and shale.

RV: Metasandstone.

Surrounding geologic terrane

Most sediment-hosted copper deposits are in terranes principally composed of sedimentary rocks.

RF: Alluvial clastic redbeds and rift-related volcanic rocks; may contain evaporites in subsurface.

RB: Alluvial clastic redbeds with or without evaporites.

RV: Precambrian alluvial and shallow marine sedimentary rocks of low metamorphic grade.

Wall-rock alteration

All models: Zones of reduced rock predate ore deposition and range from regional features extending many kilometers to local features (Shockey and others, 1974; Oszczepalski, 1989; and Hayes, 1990). Reduced zones in sandstone are bleached and contain pyrite or iron oxide pseudomorphs after pyrite; possibly formed by reducing action of fluid hydrocarbons (for example, Conel and Alley, 1984). Reduced rock is separated from oxidized rock by redox fronts (pyrite to hematite-magnetite boundaries).

Nature of ore

RF: Most ore in shale is fine-grained (typically 2 to 20 microns at White Pine, Mich., and less than 50 microns in Kupferschiefer, Poland) disseminated chalcocite accompanied by lesser amounts of native copper (White Pine) and chalcopyrite and bornite (Kupferschiefer); disseminated ore is accompanied by coarse-grained aggregates, lenses, and veinlets of native copper (White Pine) and chalcocite (Kupferschiefer) (Ensign and others, 1968; Haranczyk, 1972; Oszczepalski, 1989); Kupferschiefer sandstone ore contains pore-filling cement of copper sulfide minerals, commonly chalcocite (Tomaszewski, 1986). Weakly metamorphosed ore is impermeable; shale ore is fissile and friable.

RB: Most ore is composed of malachite, azurite, and chalcocite in sandstone pore space; some ore minerals replace fossil plant remains; most ore is porous and friable (Woodward and others, 1974; LaPoint, 1976).

RV: Ninety percent of ore contains disseminated sulfide minerals, including chalcocite and bornite, that replace sandstone cement or fill pore space; crowded, disseminated sulfide minerals form clots that replace sand grains, follow bedforms, and form ore rods across stratification; minor amount of ore is present in veins; ore is hosted by refractory quartzite (Hayes and Einaudi, 1986).

Deposit trace element geochemistry

RF: Lead, silver, and zinc abundances are locally significantly elevated; cobalt is a coproduct in Zaire-Zambian deposits; metals associated with organic matter in Kupferschiefer, Poland, include arsenic, bismuth, chromium, cobalt, gold, molybdenum, nickel, uranium, and platinum-group elements (Przybylowicz and others, 1990).

RB: Lead, silver, uranium, and vanadium are locally abundant in individual deposits; trace elements present in

Table 2.--Ore and gangue mineralogy for representative deposits of RF-, RB-, and RV-models; all data expressed as volume percent. c, common; p, present; --, not reported

Mineral	White Pine (RF) ¹	Creta (RF) ²	1-New Mexico (RB) ³	2-New Mexico (RB) ³	Spar Lake (RV) ⁴
Quartz	20-30	10-20	35-51	63-66	60-70
1-Silicate ⁵	30-35	45-63	21-39	8-17	10-20
2-Silicate ⁶	24-34	5-6	c	c	1-4
Carbonate	c	0.1-3	2-11	1-6	0.1-4
Sulfate	--	3-28	0-10	0-1	p
Hematite	0-5	--	2-9	2-8	<0.5 ⁷
Carbonaceous matter	0.5	0.3	c	c	--
Oxidized ore minerals	-	c	1-11	3-10	p ⁸
Sulfide	0-8	2-4	0-7	2-7	0.2-0.7 ⁸

¹Ensign and others (1968); in addition, they list 7 percent as "other", which includes laumontite cement and trace amounts of zircon and tourmaline (Daniels, 1982).

²Johnson (1976).

³1-N. Mex., Permian host rocks; 2-N. Mex., Triassic host rocks; data from LaPoint (1979, tab. 1); includes carbonate clasts in Permian rocks.

⁴Hayes and Einaudi (1986); quartz and feldspar from author's data on unmineralized Revett Formation.

⁵Minerals that weather at slow to very slow rates: mainly plagioclase, K-feldspar, muscovite, and clay minerals.

⁶Minerals that weather at intermediate rates: mainly chlorite, epidote, biotite, and hornblende.

⁷Also includes authigenic magnetite and leucoxene.

⁸Oxidized ore confined to outcrops and fractures; sulfide minerals adjacent to ore include as much as 0.3 percent chalcopyrite.

anomalous abundances include arsenic, barium, chromium, cobalt, molybdenum, nickel, selenium, strontium, tin, vanadium, and zinc (Lange, 1975).

RV: Lead and silver are abundant; silver is a coproduct; trace elements present in anomalous abundances include barium, boron, cadmium, chromium, cobalt, mercury, nickel, scandium, vanadium, and zinc (Lange, 1975).

Ore and gangue mineralogy, zoning

Ore and gangue mineralogy: Gangue assemblages associated with these deposits are summarized in table 2. The abundance of carbonate minerals and minerals that weather at intermediate rates, principally chlorite- and epidote-group minerals, define the acid-neutralizing capacity of these deposits (Kwong, 1993). Exceptional among RB deposits, those at Nacimiento, N. Mex., contain very small amounts (0 to 1 volume percent) of carbonate minerals (LaPoint, 1979).

Sulfide ore mostly consists of chalcocite with or without minor to locally abundant bornite, chalcopyrite, native copper, galena, sphalerite, and silver minerals. Oxidized ore, abundant only in near-surface RB deposits, is composed of malachite, azurite, chrysocolla, and cuprite.

Pyrite content: RF--Most ore has low pyrite content; beyond ore, reduced shale and siltstone may contain 1 volume percent or more pyrite. The Precambrian Nonesuch Formation near White Pine, Mich., contains 0.5 to 3 volume percent pyrite (Daniels, 1982, p. 120)). RB--Ore has low pyrite content; no reliable data. RV--Ore has low pyrite content; beyond ore, reduced Revett Formation contains about 0.1 to 0.2 volume percent pyrite (Hayes and Einaudi, 1986).

Zoning: Three types of zoning have been identified: (1) preore reduced and oxidized zones in host formations, described in section above entitled "Wall-rock alteration", (2) mineralogical zoning in primary ore, formed during hypogene deposition of sulfide minerals, and (3) secondary ore zones above primary ore, formed by near surface supergene alteration, described below in section entitled "Secondary mineralogy."

Preore redox fronts control location of some deposits; richest sulfide ore is in reduced rock near redox fronts in RF Kupferschiefer, Poland, deposits (Oszczepalski, 1989), RB Paoli, Okla., deposit (Shockey and others, 1974), and RV Spar Lake, Mont., deposit (Hayes, 1990). Primary ore zoning is observed mainly in RF and RV deposits; zoning upward and outward from the bottom of the orebody is defined by increasing solubility in the sequence chalcocite-bornite-chalcopyrite-galena-sphalerite. In some reduced facies deposits, such as White Pine, Mich., native copper is present at the base. Primary zoning commonly is attenuated laterally along bedding and condensed vertically across bedding; successively higher and distal zones in single mine faces are persistent for many kilometers laterally. Primary sulfide mineral distribution zonation generally is not reported for RB deposits, perhaps because

it has been overprinted by secondary ore.

Mineral characteristics

Textures: Sulfide minerals, interlocked with gangue (see section above entitled "Nature of ore") range from 2 to 50 microns in shale to 2 to 4 mm in sandstone ore; shale ore must be milled to fine particle size to enable metal recovery by flotation (Finlay, 1968, p. 171).

Trace element contents: RV--Trace amounts of cobalt and zinc are present in pyrite and sphalerite, respectively (Hayes and Einaudi, 1986).

General rates of weathering: Weathering rates depend on overall physical characteristics of rock: RB sandstone ore (fast) > RF shale ore > RF metamorphosed shale ore > RV quartzite ore (slow).

Secondary mineralogy

RF and RV: Outcrops include sparse stains and fracture fillings of malachite and azurite.

RB: Secondary ore, formed above water table, consists mainly of malachite, azurite, and chrysocolla. A thin zone that contains minor amounts of cuprite, native copper, native silver, and other minerals has been reported at the interface between oxidized and chalcocite ore at Nacimiento, N. Mex. (Woodward and others, 1974). Zones of chalcocite enrichment below the water table have not been reported. Jarosite and natrojarosite are present along faults at Lisbon Valley, Utah (Schmitt, 1967), but a supergene origin has not been established.

Topography, physiography

RF: Shale hosts are poorly exposed and do not form topographic features.

RB and RV: Some sandstone host rocks form cliffs and escarpments. RV deposits are in mountainous terrane.

Hydrology

RF: Ore deposits and host formations have low permeability and therefore do not channel water flow. Fracture zones along faults and permeable aquifer beds above and below ore may allow high-volume water entry from rivers, lakes, and tailings ponds. Examples: White Pine, Mich., mine pumps 3.8 million liters/day; Konkola, Zambia, mine receives major inflow from fracture zones that connect with a river and a tailings lake; it is one of the world's wettest mines (Mulenga and de Freitas, 1991).

RB: Near-surface deposits are permeable, which allows direct recharge. Faults may focus ground water flow locally. Permeable sandstone hosts may serve as regional aquifers (for example see, Mosier and Bullock, 1988).

RV: Ore deposits and host formations have low permeability and therefore do not focus flow; surface recharge is limited to fractured zones along faults; water flows down fractures and out mine workings.

Mining and processing methods

RF: These deposits are mined by underground room-and-pillar method to depths of 1,000 m; in a few old mines, longwall methods were employed. Ore is processed by pulverizing and flotation; concentrates are smelted nearby or shipped to distant smelters (E&MJ, 1979a; 1986a,b). Some Zambian ore is mined by open-pit methods and processed by combination of flotation-smelting and SX-EW methods (E&MJ, 1979a). Chalcocite in fractured and vesicular basalt flows (Model 23, Cox and Singer, 1986) has been successfully processed by *in situ* leaching (Johnson and others, 1988).

RB: These deposits are mined in small adits, inclines, and shafts; larger deposits are mined by open-pit methods. Historically, ore has been processed by pulverizing and flotation; concentrates were shipped to smelters (Soule, 1956; Talbott, 1974). Ore produced in the future will probably be processed by heap leach-SX-EW recovery of copper metal on site (for example, Mining Record, 1995).

RV: These deposits are mined by underground room-and-pillar methods; ore has been processed by pulverizing and flotation near mine site; concentrates have been shipped to smelters (E&MJ, 1979b; U.S. Forest Service and others, 1992).

ENVIRONMENTAL SIGNATURES

Drainage signatures

Mine and processing facilities: All models--These deposits resemble low-sulfide mineral, carbonate-hosted ore described by Plumlee and others (1993). Accordingly, as might be predicted from the mineralogy of these deposits, water draining mines and tailings has near-neutral to moderately alkaline pH and low dissolved metal contents (table

Table 3.--pH and dissolved metal content of mine and tailings water from some sediment-hosted copper deposits.

Mine (deposit model)	Water source	pH	Zn ($\mu\text{g/l}$)	Pb($\mu\text{g/l}$)	Cu ($\mu\text{g/l}$)
White Pine, Mich. (RF)	tailings basin ¹	7.2	--	--	--
Kupferschiefer, Germany (RF) ²	mine	6.9-7.7	--	--	--
Spar Lake, Mont. (RV) ³	mine	7.2-7.6	10-40	10	10-280
Montanore, Mont. (RV) ³	mine	7.5-8	10-20	<10	<10
Montanore, Mont. (RV) ³	settling pond	7.7-10.9	<20-50	<10	<10-20

¹Basin also receives drainage from smelter slag pile and water pumped from mine.

²Knitzschke and Kahmann (1990).

³U.S. Forest Service and others (1992, tabs. 6-10, 6-11, 6-12, and 6-14); they also report <5 $\mu\text{g/l}$ dissolved arsenic, <1 $\mu\text{g/l}$ dissolved cadmium, and <0.2 $\mu\text{g/l}$ mercury.

3). RF--Where mining, milling, and smelting are conducted on-site, water from multipurpose basins (tailings, mine, and slag pile drainage) may contain mercury, copper, cadmium, and arsenic. RB--Visually obvious suspended iron oxyhydroxide particulates, which usually indicate acid drainage, are present at some deposits. Natural concentrations of arsenic, chromium, selenium, and uranium in redbed hosts of central Oklahoma aquifer are probable sources of drinking water contamination (Mosier, in press). RV--These deposits have low dissolved metal (Al, As, Cd, Cr, Cu, Fe, Pb, Mn, Hg, Ag, and Zn) abundances but elevated total metal (including iron, manganese, and aluminum as particulate oxyhydroxide minerals; and particulate-sorbed copper, cadmium, lead, and zinc) abundances in adit drainage and water from tailings and settling ponds (U.S. Forest Service and others, 1992). Blasting operations have contributed nitrates and ammonia to stream water.

Natural drainage: Data from streams draining Revett and other formations of Belt Supergroup suggest near-neutral pH and low dissolved metals (U.S. Forest Service and others, 1992).

Metal mobility from solid mine waste

All models: Metal mobility from these deposits is low to moderate, primarily because of acid buffering capacity provided by associated carbonate rocks. Dissolved metals may be sorbed from acid drainage by suspended iron oxyhydroxide particulates (Smith and others, 1993) in drainage from open pits and mill tailings. Particulates and sorbed metals are subsequently removed from water by filtration through soil and by plant uptake (U.S. Forest Service and others, 1992).

Soil, sediment signatures prior to mining

All models: Soil and stream sediment associated with some of these deposits contains anomalous abundances of copper, lead, silver, and possibly arsenic, mercury, and zinc. Copper clearings, in which soil is copper rich and normal vegetation is replaced by copper-resistant and copper-accumulating plants, are present in the vicinity of Zaire-Zambian deposits (Reilly, 1967; Reilly and Stone, 1971; Malaisse and others, 1978). Copper (Cu^{++}) is preferentially adsorbed by organic matter and manganese in mildly acid soil (McLaren and Crawford, 1973).

RV: Soil and sediment associated with some of these deposits contain anomalous metal abundances, including >50 to as much as 2,000 ppm copper, >150 ppm lead, and >0.5 ppm silver (Cazes and others, 1981; Wells and others, 1981).

Potential environmental concerns associated with mineral processing

All models: Surface disturbance results from construction of facilities including conveyors, roads, transmission lines, mills, and tailings ponds. Local surface water may be diverted by facilities or used for milling. Drainage from processing sites may contain elevated concentrations of arsenic, cadmium, chromium, copper, mercury, and lead. Ammonia and nitrate contributed by blasting are of less concern. Acid mine and mill tailings drainage may develop if inadequate buffering capacity is provided by available carbonate rock. Organic compounds used as flocculents during milling may be toxic (for example see, U.S. Forest Service and others, 1992, p. 262). Air quality in vicinity of facilities may be affected by significant emission of suspended particulates, nitrogen oxides, sulfur dioxide, carbon monoxide, and hydrocarbons (for example see, U.S. Forest Service and others, 1992, tab. 6-2).

RF and RV: Lake levels may be disturbed if underground workings intersect fractured rock beneath lakes (U.S. Forest Service and others, 1992).

RF and RB: Additional surface disturbance may result from open pits and leaching facilities.

Smelter signatures

Smelters associated with these deposits may contribute particulates, metals, and sulfur dioxide to the environment. At White Pine, Mich., 1990 emissions were approximately 900 tonnes/year (t/yr) of particulates and about 225 t/yr of metal. Estimated outputs include 198 t/yr copper, 25 t/yr lead, 9 t/yr arsenic, 1.8 t/yr cadmium, and <1 t/yr each of chromium, mercury, and nickel (Anonymous, 1990). The stack plume at White Pine had 60 to 80 percent opacity in 1990. Most smelters control sulfur dioxide emissions by recovery as sulfuric acid (E&MJ, 1986a). Some ore is amenable to SX-EW, which avoids smelting. RB and RV ore concentrates are shipped to distant smelters.

Climate effects on environmental signatures

The effects of various climate regimes on the geoenvironmental signature specific to sediment-hosted copper deposits are not known. However, in most cases the intensity of environmental impact associated with sulfide-mineral-bearing mineral deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell. Extreme leaching of heavy metals from soil is expected in tropical environments.

Geoenvironmental geophysics

Naturally heavy-metal-distressed areas (Bolviken and others, 1977) associated with uranium and copper deposits have been delineated by the Landsat Multispectral Scanner. Airborne remote sensing (Watson and Knepper, 1994) should be applicable to mapping environmental effects of mining and processing. A variety of methods, including gravity, magnetics, electrical, and electromagnetics can be employed to define fluid migration pathways such as buried stream channels or fault zones. Induced polarization methods can be used to estimate sulfide mineral content of unmined rock. Plumes with sufficiently high metal contents can be traced using electrical or induced polarization surveys.

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REFERENCES CITED

- Anonymous, 1990, Particulate and metals emissions testing at Copper Range Company in White Pine, Michigan: Michigan Department of Natural Resources, Executive summary of Almega Corporation Report I-6764-1, unpaginated.
- Balla, J.C., 1992, Planning and permitting exploration and underground mine in environmentally sensitive areas, Troy and Rock Creek projects, northwestern Montana, U.S.A., *in* Minerals, Metals, and the Environment: Institution of Mining and Metallurgy, London, England, p. 535-546.
- _____, 1993, Geology of the Rock Creek deposit, Sanders County, Montana, *in* Belt Symposium III, August 14-21, 1993, Whitefish, Montana, Program and abstracts: Belt Association, Inc., Spokane, Washington, unpaginated.
- Bolviken, B., Honey, F., Levine, S.R., Lyon, R.J.P., and Prelat, A., 1977, Detection of naturally heavy-metal-poisoned areas by Landsat-1 digital data: *Journal of Geochemical Exploration*, v. 8, p. 457-471.
- Cazes, D.K., Domenico, J.A., Hopkins, D.M., and Leach, D.L., 1981, Geochemical analysis of stream sediments and heavy mineral concentrates collected near a stratabound Cu-Ag occurrence in the Cabinet Mountains wilderness, Montana: U.S. Geological Survey Open-File Report 81-665, 29 p.
- Conel, J.E., and Alley, R.E., 1984, Lisbon Valley, Utah, uranium test site report, *in* Abrams, M.J., Conel, J.E., Lang, H.R., and Paley, H.N., eds., *The Joint NASA/Geosat Test Case Project, Final Report*, pt. 2, v. 1, p. 8-1--8-158 [American Association of Petroleum Geologists Bookstore].
- Cox, D.P., 1986, Descriptive model of sediment-hosted Cu, *in* Cox, D.P., and Singer, D.A., eds., *Ore deposit models*: U.S. Geological Survey Bulletin 1693, p. 205.
- Cox, D.P., Lindsey, D.A., Mosier, D.L., and Whipple, J.W., 1992, Grade and tonnage differences among three models of sediment-hosted copper deposits, *in* 1992 Program, Northwest Mining Association Annual Meeting, Spokane, Washington, p. 22.

- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- Daniels, P.A., 1982, Upper Precambrian sedimentary rocks: Oronto Group, Michigan-Wisconsin, *in* Wold, R.J., and Hinze, W.J., eds., *Geology and tectonics of the Lake Superior basin*: Geological Society of America Memoir 156, p. 107-133.
- Dingess, P.R., 1976, Geology and mining operations at the Creta copper deposit of Eagle-Picher Industries, Inc., *in* Johnson, K.S., and Croy, R.L., eds., *Stratiform copper deposits of the Midcontinent region, a symposium*: Oklahoma Geological Survey Circular 77, p. 15-24.
- E&MJ, 1979a, Zambia: *Engineering and Mining Journal*, v. 180, no. 11, p. 146-159.
- _____ 1979b, Troy project okayed by Asarco, but may face court action: *Engineering and Mining Journal*, v. 180, no. 1, p. 37.
- _____ 1982, Asarco's Troy project producing copper and silver at a profit: *Engineering and Mining Journal*, v. 183, no. 12, p. 28.
- _____ 1986a, Poland's copper metallurgical center at Glogow: *Engineering and Mining Journal*, v. 187, no. 4, p. 38-41.
- _____ 1986b, Polish copper: *Engineering and Mining Journal*, v. 187, no. 2, p. 26-30.
- _____ 1989, Noranda and Montana Reserves develop Montana silver: *Engineering and Mining Journal*, v. 190, no. 3, p. 7.
- Ensign, C.O., White, W.S., Wright, J.C., Patrick, J.L., Leone, R.J., Hathaway, D.J., Trammell, J.W., Fritts, J.J., and Wright, T.L., 1968, Copper deposits in the Nonesuch Shale, White Pine, Michigan, *in* Ridge, J.D., ed., *Ore Deposits of the United States, 1933-1967; the Graton-Sales Volume*: American Institute of Mining, Metallurgical and Petroleum Engineers, New York, p. 460-488.
- Finlay, W.L., 1968, Silver bearing copper: New York, *Corinthian*, 356 p.
- Gomez-Trevino, E., and Edwards, R.N., 1983, Electromagnetic soundings in the sedimentary basin of southern Ontario--A case history: *Geophysics*, v. 48, no. 3, p. 311-330.
- Haranczyk, Czeslaw, 1972, Ore mineralization of the Lower Zechstein euxinic sediments in the Fore-Sudetic monocline: *Archiwum Mineralogiczne*, t. 30, p. 145-171.
- Hayes, T.S., 1990, A preliminary study of thermometry and metal sources of the Spar Lake strata-bound copper-silver deposit, Belt Supergroup, Montana: U.S. Geological Survey Open-File Report 90-0484, 30 p.
- Hayes, T.S., and Einaudi, M.T., 1986, Genesis of the Spar Lake strata-bound copper-silver deposit, Montana: Part I. Controls inherited from sedimentation and preore diagenesis: *Economic Geology*, v. 81, no. 8, p. 1899-1931.
- Horscroft, T.R.D., and Nettleton, E., 1989, Structural elements of the central basin of Zaire from seismic and potential field data: *Society of Exploration Geophysicists Expanded Abstracts*, no. 59, p. 115-118.
- Johnson, K.S., 1976, Permian copper shales of southwestern Oklahoma, *in* Johnson, K.S., and Croy, R.L., eds., *Stratiform copper deposits of the Midcontinent region, a symposium*: Oklahoma Geological Survey Circular 77, p. 3-14.
- Johnson, A.M., Carlson, D.H., Bagley, S.T., and Johnson, D.L., 1988, Investigations related to in situ bioleaching of Michigan chalcocite ores: *Mining Engineering*, v. 40, no. 12, p. 1119-1122.
- Jowett, E.C., 1986, Genesis of Kupferschiefer Cu-Ag deposits by convective flow of Rotliegende brines during Triassic rifting: *Economic Geology*, v. 81, no. 8, p. 1823-1837.
- Kirkham, R.V., 1984, Sedimentary copper, *in* Eckstrand, O.R., ed., *Canadian mineral deposit types: a geological synopsis*: Geological Survey of Canada Economic Geology Report 36, p. 27.
- _____ 1989, Distribution, settings, and genesis of sediment-hosted stratiform copper deposits, *in* Boyle, R.W., Brown, A.C., Jefferson, C.W., Jowett, E.C., and Kirkham, R.V., eds., *Sediment-hosted stratiform copper deposits*: Geological Association of Canada Special Paper 36, p. 3-38.
- Knitzschke, G., and Kahmann, H.J., 1990, Der Bergbau auf Kupferschiefer im Sangerhäuser Revier: *Glückauf*, v. 126, p. 528-548 [in German].
- Kwong, Y.T.J., 1993, Prediction and prevention of acid rock drainage from a geological and mineralogical perspective: Canada Centre for Mineral and Energy Technology, MEND Project 1.32.1, 47 p.
- Lange, Ian, 1975, Revett sulfide deposits and sandstone-type red-bed copper deposits of the southwestern United States: *Northwest Geology*, v. 4, p. 59-76.
- LaPoint, D.J., 1976, A comparison of selected sandstone copper deposits in New Mexico, *in* Johnson, K.S., and Croy, R.L., eds., *Stratiform copper deposits of the Midcontinent region, a symposium*: Oklahoma Geological Survey Circular 77, p. 80-96.

- _____. 1979, Geology, geochemistry, and petrology of sandstone copper deposits in New Mexico: Boulder, University of Colorado, Ph.D. thesis, 333 p.
- Malaisse, F., Gregoire, J., Brooks, R.R., Morrison, R.S., and Reeves, R.D., 1978, *Aeolanthus biformifolius De Wild.*: a hyperaccumulator of copper from Zaire: *Science*, v. 199, no. 4331, p. 887-888.
- Mauk, J.L., Seasor, R.W., Andrews, R.A., Nelson, W.S., and Robinson, R., 1992, An underground guide to the geology of the White Pine mine, Michigan, *in* Bornhorst, T.J., ed., *Keweenawan copper deposits of western upper Michigan*: Society of Economic Geology Guidebook Series, v. 13, p. 145-162.
- McLaren, R.G., and Crawford, D.V., 1973, Studies on soil copper II. The specific adsorption of copper by soils: *Journal of Soil Science*, v. 24, no. 4, p. 443-452.
- Mining Record, 1995, Summo successful at Lisbon Valley copper project: *The Mining Record*, v. 106, no. 5, p. 1.
- Mosier, E.L., in press, Geochemical characterization of solid-phase materials in the central Oklahoma aquifer, Oklahoma, *in* Christenson, S.C., and Carpenter, L.K., eds., *Ground-water quality of the central Oklahoma (Garber-Wellington) aquifer, Oklahoma: results of investigation*: U.S. Geological Survey Water-Supply Paper.
- Mosier, E.L., and Bullock, J.H., Jr., 1988, Review of the general geology and solid-phase geochemical studies in the vicinity of the central Oklahoma aquifer: U.S. Geological Survey Circular 1019, 18 p.
- Mulenga, S.C., and de Freitas, M.H., 1991, Groundwater flow model for Konkola underground copper mine, Zambia, *in* *African Mining '91*, Institution of Mining and Metallurgy, London England, Elsevier, p. 321-328.
- Oszczepalski, S., 1989, Kupferschiefer in southwestern Poland: sedimentary environments, metal zoning, and ore controls, *in* Boyle, R.W., Brown, A.C., Jefferson, C.W., Jowett, E.C., and Kirkham, R.V., eds., *Sediment-hosted stratiform copper deposits*: Geological Association of Canada Special Paper 36, p. 567-570.
- Plumlee, G.S., Smith, K.S., Ficklin, W.H., Briggs, P.H., and McHugh, J.B., 1993, Empirical studies of diverse mine drainages in Colorado: implications for the prediction of mine-drainage chemistry, *in* Munshower, F.F., and Fisher, S.E., Jr., co-chairmen, *Planning, rehabilitation and treatment of disturbed lands*, Sixth Billings Symposium, March 21-27, 1993, Reclamation Research Unit Publication No. 9301, p. 176-186.
- Przybylowicz, W., Kucha, H., Piestrzynski, A., Traxel, K., and Bajt, S., 1990, Micro-pixe analyses of trace elements in black shales from the lower Zechstein copper deposits, Poland: *Nuclear Instruments and Methods in Physics Research*, v. 50, p. 231-237.
- Reilly, C., 1967, Accumulation of copper by some Zambian plants: *Nature*, v. 215, no. 5101, p. 667-668.
- Reilly, C., and Stone, Jane, 1971, Copper tolerance in *Becium homblei*: *Nature*, v. 230, no. 5293, p. 403.
- Schmitt, L.J., 1967, Uranium and copper mineralization in the Big Indian Wash-Lisbon Valley mining district, southeastern Utah: New York, Columbia University, Ph.D. thesis, 149 p.
- Shockey, P.N., Renfro, A.R., and Peterson, R.J., 1974, Copper-silver solution fronts at Paoli, Oklahoma: *Economic Geology*, v. 69, no. 2, p. 266-268.
- Sinha, A.K., 1990, Stratigraphic mapping of sedimentary formations in southern Ontario by ground electromagnetic methods: *Geophysics*, v. 55, no. 9, p. 1148-1157.
- Smith, K.S., Ficklin, W.H., Plumlee, G.S., and Meier, A.L., 1993, Computer simulations of the influence of suspended iron-rich particulates on trace-metal removal from mine-drainage waters, *in* Munshower, F.F., and Fisher, S.E., Jr., co-chairmen, *Planning, rehabilitation and treatment of disturbed lands*, Sixth Billings Symposium, March 21-27, 1993, Reclamation Research Unit Publication No. 9301, p. 107-115.
- Soule, J.H., 1956, Reconnaissance of the "Red Bed" copper deposits in southeastern Colorado and New Mexico: U.S. Bureau of Mines Information Circular 7740, 74 p.
- Spanski, G.T., 1992, Quantitative assessment of future development of copper/silver resources in the Kootenai National Forest, Idaho/Montana: Part 1—Estimation of the copper and silver endowments: *Nonrenewable Resources* v. 1, no. 2, p. 163-183.
- Talbott, L.W., 1974, Nacimiento pit, a Triassic strata-bound copper deposit, *in* *New Mexico Geological Society Guidebook*, 25th Annual Field Conference, p. 301-303.
- Tomaszewski, J.B., 1986, Comments on the genesis and structure of copper-polymetallic ore deposit of the Foresudetic monocline, SW Poland, *in* Harwood, G.M., and Smith, D.B., eds., *The English Zechstein and related topics*: Geological Society Special Publication No. 22, p. 183-194.
- Unrug, R., 1989, Landsat-based structural map of the Lufilian Fold Belt and the Kundelungu Aulacogen, Shaba (Zaire), Zambia, and Angola, and the regional position of Cu, Co, U, Au, Zn, and Pb mineralization, *in* Boyle, R.W., Brown, A.C., Jefferson, C.W., Jowett, E.C., and Kirkham, R.V., eds., *Sediment-hosted stratiform copper deposits*: Geological Association of Canada Special Paper 36, p. 519-524.

- U.S. Forest Service, Montana Department of State Lands, Montana Department of Health and Environmental Sciences, and Montana Department of Natural Resources, 1992, Noranda Minerals Corp.-Montana Reserves Company Joint Venture, Montanore project: Final Environmental Impact Statement, v. 1, 625 p.
- Volodin, R.N., Chechetkin, V.S., Bogdanov, Yu.V., Narkelyun, L.F., and Trubachev, A.I., 1994, The Udokan cupriferous sandstones deposit (eastern Siveria): *Geology of Ore Deposits*, v. 36, no. 1, p. 1-25.
- Watson, Ken, and Knepper, D.H., eds., 1994, Airborne remote sensing for geology and the environment--present and future: U.S. Geological Survey Bulletin 1926, 43 p.
- Wells, J.D., Domenico, J.A., Frisken, J.G., and Hopkins, R.T., 1981, Geochemical survey of the Cabinet Mountains wilderness, Lincoln and Sanders Counties, Montana, *in* U.S. Geological Survey and U.S. Bureau of Mines, Mineral resources of the Cabinet Mountains wilderness, Lincoln and Sanders Counties, Montana: U.S. Geological Survey Bulletin 1501, p. 25-51.
- Woodward, L.A., Kaufman, W.H., Schumacher, O.L., and Talbott, L.W., 1974, Strata-bound copper deposits in Triassic sandstone of Sierra Nacimiento, New Mexico: *Economic Geology*, v. 69, no. 1, p. 108-120.
- Zohdy, A.A.R., Eaton, G.P., and Mabey, D.R., 1974, Electrical methods, *in* Techniques of water-resources investigations of the U.S. Geological Survey, Application of Surface Geophysics to Groundwater Investigations: Book 2, Chapter D1, p. 5-66.

SEDIMENTARY EXHALATIVE ZN-PB-AG DEPOSITS (MODEL 31a; Briskey, 1986)

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SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Lens-like bodies of stratiform sulfide minerals (lead, zinc, \pm iron) as much as a few tens of meters in thickness are interbedded with fine-grained dark clastic and chemical sedimentary rocks. These deposits may have large lateral extent (hundreds of meters to kilometers). Mineralized rock varies from a single layer to numerous bodies that may be vertically stacked or lateral equivalents. The most common associated sulfate mineral is barite which may be peripheral to or stratigraphically above the deposit (Rammelsberg and Meggen, Germany; Tom, Yukon Territory; Lady Loretta, Australia; and Red Dog, Alaska), or it may form crudely segregated mixtures with sulfide minerals (Cirque, British Columbia). Many deposits have no associated barite (HYC, Australia; Sullivan, British Columbia; and Howard's Pass, Yukon Territory). Stockwork, disseminated, or vein-type ore, interpreted as feeder zones to stratiform mineralized rock, are sometimes found underlying or adjacent to stratiform ore and are sometimes accompanied by alteration of footwall rocks (fig. 1). U.S. Bureau of Mines (1993) statistics show that in 1993 the two mines in the United States with greatest zinc output were Red Dog, Alaska and Balmat, N.Y. In 1994, the Red Dog mine produced 533,500 t of zinc concentrate with an average grade of 55.8 weight percent zinc (Mining Journal, 1995). Mines in the Balmat district produced 499,000 t in 1993. Both mines also produce lead and silver.

Examples

Red Dog, Lik, and Drenchwater (Alaska); Balmat (N.Y.); Meggen and Rammelsberg (Germany); Faro and other deposits in the Anvil district, Tom, Jason, and Howard's Pass (Yukon Territory); Cirque and Sullivan (British Columbia); Lady Loretta, McArthur River, Mount Isa, HYC, and Broken Hill (Australia); Navan, Silvermines, and Tynagh (Ireland); Black Mtn., Broken Hill, Big Syncline (South Africa); Zawar (India).

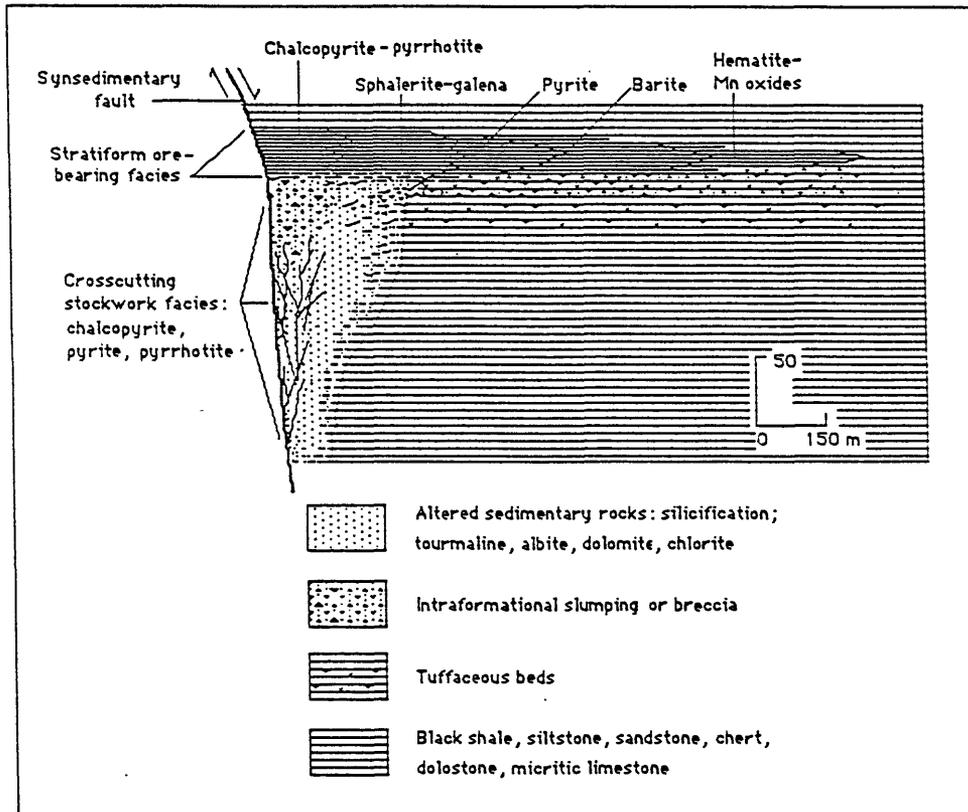


Figure 1. Diagrammatic cross section showing mineral zoning in sedimentary exhalative Zn-Pb deposits (from Briskey, 1986).

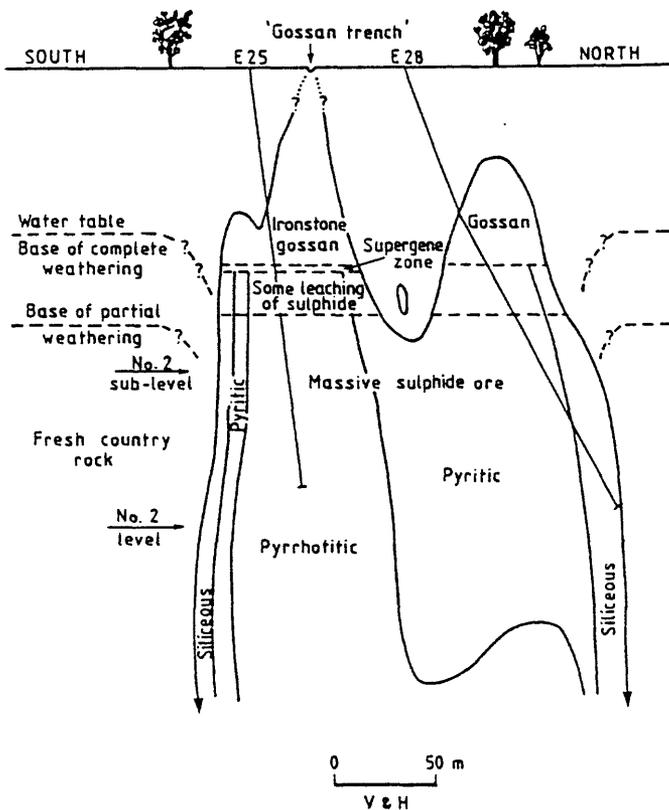


Figure 2. Longitudinal cross section showing development of supergene zone and iron-rich gossan (based on Elura deposit, Australia; from Taylor and others, 1984).

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include bedded barite deposits (Model 31b), stratabound lead-zinc in clastic rocks (Model 30a), Mississippi Valley type lead-zinc (Models 32a,b), sedimentary manganese (Model 34b), sedimentary phosphate (Model 34c), Besshi massive sulfide (Model 24b), Chinese-type black shale (Mo-Ag-As-Zn-Ni-PGE; Pasava, 1993).

Potential environmental considerations

- (1) Deposits with no associated carbonate rocks or carbonate alteration minerals may have high potential for generation of natural acid drainage that contains high metal concentrations. Potential for acid-drainage generation may depend on (a) the amount of iron-sulfide present (which may vary from <5 to 80 volume percent among deposits), (b) the type of iron sulfide mineral(s) in the deposit (reactivity decreases from pyrrhotite to marcasite to pyrite) and (c) the extent to which the deposit is exposed to air and water. Water may contain thousands of mg/l sulfate; hundreds of mg/l iron; tens of mg/l aluminum; thousands to tens of thousands of $\mu\text{g/l}$ zinc; thousands of $\mu\text{g/l}$ manganese and lead; hundreds of $\mu\text{g/l}$ cadmium, copper, and nickel; and tens of $\mu\text{g/l}$ cobalt (Runnells and others, 1992; Kelley and Taylor, in press; EIS for Red Dog).
- (2) Potential downstream environmental effects of natural acid drainage can be significant in magnitude and spatial extent (as far as 30 km downstream), especially if surrounding terrane is composed exclusively of fine-grained clastic rocks and volcanic rocks and no associated carbonate rocks (EIS for Red Dog).
- (3) Deposits with associated carbonate rocks or abundant carbonate alteration minerals have limited potential for acid drainage generation (water pH usually neutral to slightly alkaline), and most metal concentrations are low; exceptions include as much as thousands of $\mu\text{g/l}$ zinc in some natural water (Kelley and Taylor, in press).
- (4) Iron-rich gossans, formed by oxidation and weathering, may develop above some deposits (fig. 2). Depending on wall-rock buffering capacity, iron content of ore, and metal-sulfur ratios of sulfide minerals, the gossan environment can be acidic (pH <5). Some gossans may contain a number of secondary lead-manganese minerals as well as secondary sulfates of iron, aluminum, and potassium (Taylor and others, 1984). These minerals are very soluble, can dissolve during periodic storms, and may lead to short term pulses of highly acidic, metal-bearing water.
- (5) High-sulfide ore with elevated abundances of pyrrhotite that is exposed to air and water has potential for spontaneous combustion ("hot muck"), which generates sulfur dioxide (Brown and Miller, 1977; Good, 1977). Hot muck ignition is rare and can be avoided using proper blasting techniques.

Exploration geophysics

Gravity surveys can be used to identify and delineate the extent of barite-rich zones that may indicate associated base-metal sulfide deposits (Young, 1989; Hoover and others, 1994). Induced polarization methods have proven useful in exploration for some of these deposits (O'Brien and Romer, 1971; Cox and Curtis, 1977). Remote sensing images can be used to help identify associated gossans (Knepper, 1989). Magnetic and electromagnetic methods may help define the presence and extent of massive sulfide deposits, particularly those that contain abundant pyrite and (or) pyrrhotite. Constant source-audiomagnetotelluric methods have been used to help delineate the extent of ore in northwest Alaska (Young, 1989). Other geophysical methods may facilitate geologic mapping of these deposits (Edwards and Atkinson, 1986, p. 245).

References

Geology: Large (1981), Maynard (1983), Sangster (1983), Moore and others (1986), Turner and Einaudi (1986), Young (1989), Sangster (1990), Maynard (1991), and Schmidt (in press).
Environmental geology, geochemistry: Lee and others (1984), Runnells and others (1992), Gulson and others (1994), Prusty and others (1994), Sahu and others (1994), Kelley (1995), and Kelley and Taylor (in press).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Most deposits are 1.7 (90th percentile) to 130 (10th percentile) million tons; median deposit size is 15 million tons (Menzie and Mosier, 1986).

Host rocks

Host rocks consist of a variety of marine sedimentary rocks including: carbonaceous shale and chert (Howard's Pass, Yukon Territory; Red Dog and Lik, Alaska; and Sullivan, British Columbia), dolomitic shale or siltstone (HYC and Mount Isa, Australia; and Silvermines, Ireland), and micritic limestone (Meggen, Germany and Tynagh, Ireland). Turbidites and slump breccias are present locally; minor volcanic rocks, usually mafic, may be temporally, but not necessarily spatially, associated. Sangster (1990) indicates that tuff units are present within ore-hosting sequences at a number of deposits, including Meggen and Rammelsberg (Germany), Jason and Faro (Yukon Territory), and HYC (Australia). Many deposits and their host rocks have undergone metamorphism and deformation (Sullivan, British Columbia and Mount Isa and Broken Hill, Australia). Comparisons of host rock chemistry to average abundances in black shale (Vine and Tourtelot, 1970) show that host rocks for these deposits have relatively low sodium-potassium ratios and are characteristically depleted in cobalt, nickel, and copper and enriched in barium and manganese (Maynard, 1991).

Surrounding geologic terrane

The geologic terrane surrounding these deposits primarily consists of thick sequences of deep-water marine sedimentary rocks that include fine-grained clastic and carbonate rocks. Rocks may be metamorphosed (low to high-grades).

Wall-rock alteration

Stockwork and disseminated sulfide and alteration minerals (commonly silicified or iron-carbonate altered rocks that rarely contain tourmaline, albite, chlorite), which possibly represent the feeder zones of these deposits, are sometimes present beneath or adjacent to stratiform deposits (fig. 1). In some deposits, silicification is the dominant or only alteration (Meggen, Germany and Red Dog, Alaska). In others, alteration is less extensive and (or) carbonate-rich (Large, 1981). Large (1983) describes more subtle types of alteration near some deposits, including increased dolomite-calcite ratios (McArthur River, Australia; deposits in Ireland) and increased potassium feldspar-albite ratios in tuffs (McArthur River).

Nature of ore

Within stratiform mineralized rocks, sulfide minerals are generally fine-grained, and commonly form nearly monomineralic laminae several mm to cm thick that have continuity over large parts of the deposits. Some deposits are not laminated (Meggen, Germany and Red Dog, Alaska). Coarse-grained crustiform and comb-textured sulfide minerals may be present in feeder veins associated with stratiform ore. The overall sheet or lens-like morphology of stratiform ore suggests that these deposits formed, in highly restricted basins, by syngenetic to early diagenetic

processes at or below the seawater-sediment interface. Sphalerite, galena, and iron-sulfide minerals (pyrite, marcasite, and pyrrhotite) are the most common sulfide minerals, but chalcopyrite and sulfosalt minerals may also be present in minor amounts (Large, 1981; 1983; Lydon, 1983).

Deposit trace element geochemistry

Feeder or stockwork zone (Large, 1983; Lydon, 1983): iron, lead, and zinc (\pm gold, boron, and copper). Stratiform ore (Large, 1983; Lydon, 1983): lead, zinc (cadmium), with or without barium (zoned laterally outward from feeder zone (fig. 1). Iron may be enriched within and adjacent to the base-metal sulfide zone (Large, 1983); anomalous concentrations of silver \pm arsenic and antimony in sulfosalt minerals (Cox and Curtis, 1977; Taylor and others, 1984) and manganese (outer halo) are also common (Maynard, 1981). Concentrations of mercury are high in some deposits, where it is primarily in pyrite, sphalerite, or sulfosalt minerals (Ryall, 1981).

Ore and gangue mineralogy and zonation

Dominant sulfide ore minerals are sphalerite and galena, although minor chalcopyrite, arsenopyrite, and tetrahedrite are present in some deposits (Large, 1983). The most common gangue minerals are iron sulfide (pyrite or marcasite; less commonly pyrrhotite) and quartz (Meggen, Germany and Red Dog, Alaska). Barite may be present. Numerous other sulfide and sulfosalt minerals have been reported in some deposits (Cox and Curtis, 1977; Large, 1983; Taylor and others, 1994). Relative abundances of major base-metal sulfide minerals vary among deposits and within deposits as a result of zonation. Large (1983) reports that lead-zinc ratios of ore range from approximately 1:1 (Mount Isa, Australia; Sullivan, British Columbia; and Tynagh, Ireland) to 1:8 (Meggen, Germany). The sequence of zonation is generally lead-zinc-(barium-copper) extending outward in laterally zoned deposits and zinc-lead-(barium) extending upward in vertically zoned deposits (Large, 1983; Lydon, 1983). Iron is sometimes enriched at the center of zonation assemblages (for instance, Rammelsberg, Germany and Sullivan, British Columbia) (Large, 1983), or an iron-manganese halo may encircle the base-metal sulfide minerals (Tynagh, Ireland) (Maynard, 1983).

Mineral characteristics

Grain size typically ranges from 15 to 400 microns (McClay, 1983). Primary depositional features are dominated by fine-grain size and common layering; framboidal and colloform pyrite with euhedral overgrowths are common; granular sphalerite, galena and barite are typical. Some deposits (Red Dog, Alaska and HYC, Australia) are characterized by very fine-grained intergrowths of silica and sphalerite (individual sphalerite grains are 0.5 to 50 microns) or sphalerite with other sulfide minerals (<100 microns) (McClay, 1983; Moore and others, 1986). Metamorphism partially or completely replaces primary textures and causes grain size increases. Recrystallization causes porphyroblastic textures in pyrite and sphalerite, barite is recrystallized to an elongate habit, and galena may be remobilized to fill fractures (McClay, 1983).

Secondary mineralogy

Oxidation of deposits may result in formation of iron-rich gossan and ferruginization of wall rocks (fig. 2). Deposits with low iron-sulfide contents have high metal-sulfur ratios, gangue or wall rocks with high buffering capacity, associated gossans have high pH, and gossan profiles are immature. Ore with high iron content, low metal-sulfur ratios in sulfide minerals, and wall rock with low buffering capacity is likely to be associated with low pH water (Taylor, 1984). Goethite and hematite, with minor quartz, kaolinite, and beudantite, are the main minerals in gossan (Taylor and others, 1984). Anglesite and cerussite are the most abundant secondary lead minerals but coronadite, mimetite, nadorite, pyromorphite, and lanarkite have also been reported. Silver halide minerals may also be present. Secondary zinc minerals are rare. Secondary sulfate minerals include jarosite, barite, and alunite. Native sulfur, produced by oxidation of marcasite, is present at Red Dog, Alaska (R.A. Zierenberg, written commun., 1995). Rock may be oxidized to 100 m below the surface (Australian examples), and may extend to 300 m adjacent to major faults and shear zones. Oxidation depth is controlled partly by fracture density near orebodies and presence of pyrrhotite, which is highly reactive with oxygenated ground water (Taylor and others, 1984).

Secondary zinc minerals hemimorphite, smithsonite, and wurtzite, not found in association with other deposits, are present in lime green mosses and as a cement within talus overlying the XY deposit (Howard's Pass, Yukon Territory) (Jonasson and others, 1983; Lee and others, 1984).

Topography, physiography

No generalizations possible. Sedimentary exhalative deposits are widely distributed geographically (from Australia to northern Alaska, to Ireland, for example) and so have completely different physiographies and topographies due

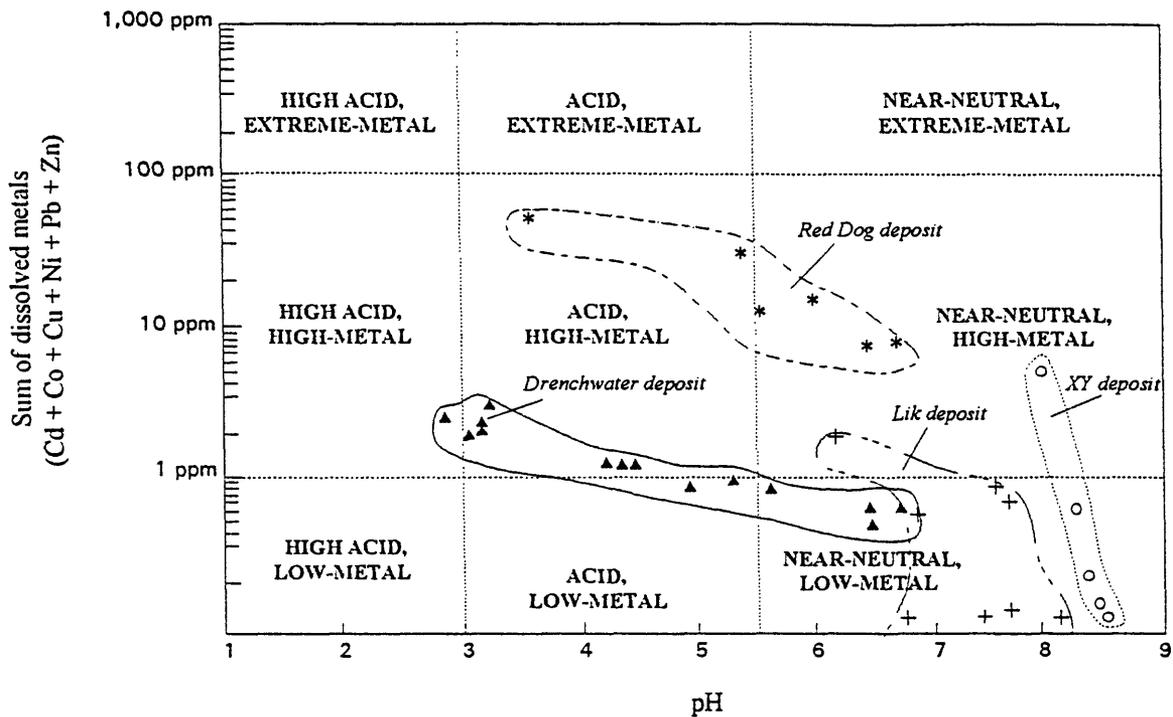


Figure 3. Diagram showing the relation between pH and metal content of water draining sedimentary exhalative deposits (modified from Plumlee and others, 1993).

to weathering process variations.

Hydrology

Hydrologic conditions associated with sedimentary exhalative deposits are highly variable due to extreme differences of their climate settings. Fine-grained clastic host rocks generally have low permeability. Pre-mineralization and post-mineralization fractures may serve as ground water conduits. However, depth of oxidation is dependant on a number of factors including climate, mineralogy of ore, and (or) host rocks.

Mining and milling methods

Underground and open-pit mining have been used historically and in modern times to exploit these deposits. Some sedimentary exhalative deposits contain very fine-grained and intergrown sulfide minerals (for example, Red Dog, Alaska and HYC, Australia) that require fine grinding during ore beneficiation. Base metal sulfide minerals are usually separated by flotation and ore concentrates are smelted. In most cases, concentrates are shipped to custom smelters and therefore do not contribute to environmental impact in the immediate mine vicinity. Large districts, such as Sullivan, British Columbia, are served by nearby smelters (for instance, Trail smelter, British Columbia).

ENVIRONMENTAL SIGNATURES

Drainage signatures

Natural drainage water (Lik, Red Dog, and Drenchwater, Alaska: Dames and Moore, 1983; EIS report for Red Dog; Kelley, 1995; Kelley and Taylor, in press): Cold semi-arid climate--Without carbonate rocks present (Red Dog and Drenchwater), streams draining mineralized areas have low pH (2.8 to 4.7) and elevated dissolved metal abundances, including tens to hundreds of mg/l aluminum and iron and hundreds to tens of thousands of $\mu\text{g/l}$ Mn, Cd, Co, Cu, Ni, Pb, and Zn. Sulfate concentrations, hundreds to thousands of mg/l, in water draining mineralized areas are also many times higher than background. Sodium and barium may be depleted in water draining mineralized areas. Data for deposits with significant associated carbonate rocks in surrounding geologic terrane (Lik, Alaska) are strikingly different (fig. 3). Water draining these deposits is near-neutral to alkaline (pH 6.2 to 8.1) and contains low metal concentrations, except zinc, whose abundances, thousands of $\mu\text{g/l}$, are enriched in streams draining mineralized areas. Sulfate concentrations, hundreds of mg/l, may also be elevated.

Neutral-pH springwater near the XY deposit (Howard's Pass, Yukon Territory) contains elevated dissolved metal abundances, including tens to thousands of $\mu\text{g/l}$ zinc, tens of $\mu\text{g/l}$ cadmium, and tens to hundreds of mg/l sulfate.

Mine drainage water (Red Dog, Alaska: Beelman, 1993; unpub. data, Alaska Department of Environmental Conservation, ADEC, 1995; Faro, Yukon Territory: Lopaschuk, 1979; Meggen, Germany: Bergmann, 1971; Broken Hill, South Africa: Gulson and others, 1994): Cold semi-arid climate--Immediately after mining began at Red Dog in the Fall of 1990, water draining the mine was extremely acidic (pH as low as 1.7) and contained elevated metal abundances, including from hundreds to thousands of $\mu\text{g/l}$ lead, from hundreds to tens of thousands of $\mu\text{g/l}$ cadmium, and from tens of thousands of $\mu\text{g/l}$ to thousands of mg/l zinc. However, by spring of 1991, these abundances had decreased to pre-mining natural background concentrations (ADEC, 1995). The pulse of metal-enriched mine drainage that followed initial mining was probably the result of dissolution and flushing of a secondary sulfate mineral accumulation that developed as a result of marcasite oxidation in a near surface environment along steep faults (R.A. Zierenberg, written commun., 1995). Mild wet climate--The Meggen, Germany, mine, known in the late 1960s for mine water with high metal ion content and low pH, posed a severe pollution problem (Bergmann, 1971). Elevated metal abundances included hundreds of mg/l aluminum, tens of mg/l manganese, hundreds to thousands of mg/l iron, and hundreds to thousands of mg/l zinc. Potentially economically recoverable elements: Zinc (as zinc hydroxide produced after treatment of mine water) is economically extracted at the Meggen, Germany, mine (Bergmann, 1971).

Metal mobility from solid mine wastes

Mine dumps may be a source of lead due to soluble secondary lead minerals common in oxidized material. Some of these dumps have recently been reprocessed, resulting in an increased volume of fine-grained lead-rich dust that contains as much as 3 weight percent lead (Gulson and others, 1994); this dust can be important in arid to semi-arid regions with high wind potential.

Bioavailability studies: The most common lead species in soil and dust associated with the Broken Hill, Australia, deposit was identified as a complex Pb, Fe, Mn, Ca, Al, Si, O material (very soluble), with high bioavailability. Other mining areas may have less soluble, and therefore lower bioavailability forms of lead, including galena, pyromorphite, and anglesite (Gulson and others, 1994).

Soil, sediment signatures prior to mining

Cold semi-arid climate: Stream sediment samples (<0.2 mm and <0.5 mm fractions) contain anomalous concentrations of many metals, including as much as ten ppm silver; tens of ppm arsenic, cadmium, and antimony; hundreds of ppm copper and nickel; thousands of ppm manganese, lead, and zinc; and hundreds of thousands of ppm barium (Theobald and others, 1978; Kelley and others, 1992). Soil that overlies mineralized rock contains hundreds to tens of thousands of ppm lead, hundreds to thousands of ppm barium and zinc, tens of ppm silver; and tens to hundreds of ppm copper, but concentrations of other metals, including <2 ppm cadmium, hundreds of ppm manganese, and tens of ppm nickel are low relative to stream sediment abundances (Briggs and others, 1992; Meyer and Kurtak, 1992). The pH of soil directly above mineralized rock may be as low as 3.9 (Briggs and others, 1992).

Warm semi-arid climate (Australia): Soil overlying mineralized rock contains hundreds to thousands of ppm copper, lead, and zinc, and tens of ppm silver (Cox and Curtis, 1977).

Potential environmental concerns associated with mineral processing

Mining and milling methods significantly influence potential environmental impacts associated with sedimentary exhalative deposits. Most underground mines dispose of mine waste and mill tailings by backfilling underground workings. Consequently, environmental concerns related to these underground mines may be limited, with exceptions noted below.

Modern mines discharge fine-grained sulfide-mineral-rich tailings into surface tailings ponds that have impermeable linings. Previous tailings discharge methods resulted in significant surface and shallow ground water contamination. Very finely ground, fine-grained and intergrown sulfide minerals may result in highly reactive tailings products.

Until 1967, mine water draining the Meggen, Germany underground mine had a pH as low as 2.5 and contained as much as 1,300 mg/l zinc; this mine water originates by percolation of surface water through the mine. Acidic, metal-rich water draining the mine caused severe pollution in major river systems draining the area. Modern techniques enabled zinc recovery from mine water; mine effluent ceased to be a pollution source (Bergmann, 1971).

Mining and milling activities at the Zawar, India mine have resulted in contamination of stream sediment and floodplain soil (Prusty and others, 1994; Sahu and others, 1994). Stream sediment samples collected as much as 30 km from the mill site contain elevated metal abundances, including thousands of ppm zinc and iron, hundreds of ppm lead, and tens of ppm cadmium. Floodplain soil contains similarly elevated metal abundances.

"Hot muck" was an environmental concern associated with processing ore from deposits with high pyrrhotite abundances that are exposed to air and water. "Hot muck" is the spontaneous combustion of high sulfide ore in the mine. The primary environmental concern is evolved sulfur dioxide. Fires are ignited by the build-up of heat, caused by ore oxidation, in stock piles, or may be triggered by blasting in areas of previously broken ore. Periodically, air emission can exceed 9.5 ppm SO₂ (Brown and Miller, 1977; Good, 1977); SO₂ release can acidify water in areas downwind from release site. Because hot muck is easily avoided by proper blasting techniques, it does not pose significant risks in modern mining operations.

In some cold climates, it may be necessary to store wet ore, such as that produced from the Faro, Yukon Territory, mine, prior to crushing. If the ore is stockpiled too long, oxidation may ensue (Lopaschuk, 1979), which may cause increased metal concentrations, especially lead, in drainage water.

Smelter signatures

Smelting was and is commonly used to process sedimentary exhalative ore. Several studies focus on the correlation between lead in soil near smelters and lead in the blood of children (Gulson and others, 1994). Smelting may produce SO₂-rich and metal-rich emissions, which may increase acidity and foster accumulation of heavy metals in downwind areas.

Climate effects on environmental signatures

Sedimentary exhalative deposits are widely distributed geographically (from Australia to northern Alaska, as well as Ireland) and therefore are in highly variable climatic regimes. The effects of various climate regimes on the geoenvironmental signature specific to sedimentary exhalative deposits are not known. However, in most cases the intensity of environmental impact associated with sulfide-mineral-bearing mineral deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell. Although it is commonly assumed that the extent of sulfide mineral oxidation and weathering in cold regions underlain by permafrost are minimal, data from northern Alaska show that metal dispersion from ore deposits in surface water is significant.

Geoenvironmental geophysics

Induced polarization methods can provide qualitative estimates of sulfide mineral contents and grain size, which strongly influence potential for generation of acidic, metal-enriched water. Electrical techniques (King and Pesowski, 1993) and ground penetrating radar (Davis and Annan, 1992) can be used to delineate low resistivity anomalies produced by acidic, metal-enriched water that may be associated with this deposit type.

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REFERENCES CITED

- Alaska Department of Environmental Conservation (ADEC), 1995, unpub. data.
- Beelman, Joyce, 1993, Water quality impacts of a lead/zinc mine in northwest Alaska, *in* Magoon, O.T., Wilson, W.S., Converse, H., Tobin, L.T., eds., Coastal zone '93, Proceedings of the eighth Symposium on Coastal and Management: American Society of Civil Engineers, v. 2, p. 1911-1912.
- Bergmann, Artur, 1971, How Meggen purifies mine water and recovers marketable Zn precipitate: *World Mining*, v. 7, no. 10, p. 48-51.
- Briggs, P.H., Motooka, J.M., Bailey, E.A., Cieutat, B.A., Burner, S.A., Kelley, K.D., and Ficklin, W.H., 1992, Analytical results of soil, stream sediment, panned concentrate, and water samples from the Lik deposit, northwestern Brooks Range, Alaska: U.S. Geological Survey Open-File Report 92-15A (paper version) and 92-15B (diskette version).
- Briskey, J.A., 1986, Descriptive model of sedimentary exhalative Zn-Pb, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 211-212.

- Brown, R.L., and Miller, F.J.L., 1977, Pollution problems associated with Sullivan mine hot muck: Canadian Institute Mining and Metallurgy Bulletin, v. 70, n. 782, p. 89-92.
- Cox, R., and Curtis, R., 1977, The discovery of the Lady Loretta zinc-lead-silver deposit, northwest Queensland, Australia--A geochemical exploration case history: Journal of Geochemical Exploration, v. 8, p. 189-202.
- Cox, D.P., and Singer, D.A., 1986, Mineral deposit models: U.S. Geological Survey Bulletin 1693, 379 p.
- Dames & Moore, 1983, Environmental baseline studies, Red Dog project: Water Quality Report, Chapter 3, by L.A. Peterson and Associates, Inc., for the Red Dog Mine project, Cominco, Alaska, Inc., Anchorage, Alaska.
- Davis, J.L., and Annan, A.P., 1992, Applications of ground penetrating radar to mining, groundwater, and geotechnical projects--selected case histories: Geological Survey of Canada Paper 90-4, p. 49-55.
- Edwards, Richard, and Atkinson, Keith, 1986, Ore deposit geology: London, Chapman and Hall, 466 p.
- EIS (Environmental Impact Statement) for Red Dog.
- Good, B.H., 1977, The oxidation of sulphide minerals in the Sullivan mine: Canadian Institute of Mining and Metallurgy Bulletin, v. 70, no. 782, p. 83-88.
- Gulson, B.L., Mizon, K.J., Law, A.J., Korsch, M.J., Davis, J.J., and Howarth, D., 1994, Source and pathways of lead in humans from the Broken Hill Mining Community--An alternative use of exploration methods: Economic Geology, v. 89, no. 4, p. 889-908.
- Hoover, D.B., Hill, P.L., and Knepper, D.H., Jr., 1994, Geophysical model of bedded barite, *in* Heran, W.D., ed., Codicil to the Geophysical Expression of Selected Mineral Deposit Models: U.S. Geological Survey Open-File Report 94-174, p. 28-31.
- Jonasson, I.R., Jackson, L.E., and Sangster, D.F., 1983, A Holocene zinc orebody formed by supergene replacement of mosses: Journal of Geochemical Exploration, v. 18, p. 189-194.
- Kelley, K.D., 1995, Natural environmental effects of silver-lead-zinc deposits in the Brooks Range, Alaska: U.S. Geological Survey Fact Sheet 092-95.
- Kelley, K.D., Borden, J.C., Bailey, E.A., Fey, D.L., Motooka, J.M., and Roushey, B., 1992, Geochemically anomalous areas in the west-central part of the Howard Pass Quadrangle, National Petroleum Reserve, Brooks Range, Alaska--Evidence for sediment-hosted Zn-Pb-Ag-Ba mineralization, *in* Evans, D.C. and Dusel-Bacon, Cynthia, eds., Geologic studies in Alaska by the U.S. Geological Survey during 1991: U.S. Geological Survey Bulletin 2041, p. 60-69.
- Kelley, K.D., and Taylor, C.D., in press, Natural environmental effects associated with the Drenchwater zinc-lead-silver massive sulfide deposit with comparisons to the Lik and Red Dog deposits, Brooks Range, Alaska, *in* Dumoulin, J.A., and Moore, T.E., eds., Geologic studies in Alaska by the U.S. Geological Survey, 1994: U.S. Geological Survey Bulletin 2152.
- King, A. and Pesowski, M., 1993, Environmental applications of surface airborne geophysics in mining: Canadian Institute of Mining and Metallurgy Bulletin, v. 86, p. 58-67.
- Knepper, D.H., 1989, Mapping hydrothermal alteration with Landsat thematic mapper data, *in* Lee and others, eds., Mineral deposits of North America, v. 1, Remote sensing in exploration geology; Field trips for the 29th International Geological Congress: Washington, DC, American Geophysical Union, p. 13-21.
- Large, D.E., 1981, Sediment-hosted submarine exhalative lead-zinc deposits--A review of their geological characteristics and genesis, *in* Wolf, K.H., ed., Handbook of stratabound and stratiform ore deposits: Amsterdam, Elsevier, v. 9, p. 469-508.
- Large, D.E., 1983, Sediment-hosted massive sulfide lead-zinc deposits: an empirical model, *in* Sangster, D.F., ed., Sediment-hosted stratiform lead-zinc deposits: Mineralogical Association of Canada Short Course Handbook, v. 8, p. 1-30.
- Lee, Julian, Jonasson, I.R., and Goodfellow, W.D., 1984, Metal accumulation by bryophytes in some zinc-rich blanket bogs, Selwyn Mountains, Yukon Territory: Canadian Journal of Botany, v. 62, no. 4, p. 722-728.
- Lopaschuk, R.S., 1979, Drainage control and mine dewatering at Faro open pit mine, *in* Argall, G.O., Jr., and Brawner, C.O., eds., Mine Drainage: Proceedings of the first international mine drainage symposium, Miller Freeman Publications, p. 233-257.
- Lydon, J.W., 1983, Chemical parameters controlling the origin and deposition of sediment-hosted stratiform lead-zinc deposits, *in* Sangster, D.F., ed., Sediment-hosted stratiform lead-zinc deposits: Mineralogical Association of Canada Short Course Handbook, v. 8, p. 175-250.
- Maynard, J.B., 1983, Geochemistry of sedimentary ore deposits: Springer-Verlag, New York, New York, 305 p.

- _____. 1991, Shale-hosted deposits of Pb, Zn, and Ba: Syngenetic deposition from exhaled brines in deep marine basins, in Force, E.R., Eidel, J.J., and Maynard, J.B., eds., *Sedimentary and diagenetic mineral deposits: A basin analysis approach to exploration: Society of Economic Geologists Reviews in Economic Geology*, v. 5, p. 177-185.
- McClay, K.R., 1983, Deformation of stratiform lead-zinc deposits, in Sangster, D.F., ed., *Sediment-hosted stratiform lead-zinc deposits: Mineralogical Association of Canada Short Course Handbook*, v. 8, p. 283-309.
- Menzie, W.D., and Mosier, D.L., 1986, Grade and tonnage model of sedimentary exhalative Zn-Pb, in Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 212-215.
- Meyer, M.P., and Kurtak, J.M., 1992, Results of the 1991 U.S. Bureau of Mines Colville Mining District study: U.S. Bureau of Mines Open-File Report 75-92, 101 p.
- Mining Journal*, 1995, v. 325, no.8344, p. 189.
- Moore, D.W., Young, L.E., Modene, J.S., and Plahuta, J.T., 1986, Geologic setting and genesis of the Red Dog zinc-lead-silver deposit, western Brooks Range, Alaska: *Economic Geology*, v. 81, no. 7, p. 1696-1727.
- O'Brien, M.V., and Romer, D.M., 1971, Tara's zinc-lead discovery at Navan, Republic of Ireland: *Canadian Mining Journal*, v. 92, no. 4, p. 81-82.
- Pasava, J., 1993, Anoxic sediments; an important environment for PGE; an overview: *Ore Geology Reviews*, v. 8, no. 5, p. 425-445.
- Plumlee, G.S., Smith, K.S., Ficklin, W.H., Briggs, P.H., and McHugh, J.B., 1993, Empirical studies of diverse mine drainages in Colorado: implications for the prediction of mine-drainage chemistry, in Munshower, F.F., and Fisher, S.E., Jr., co-chairmen, *Planning, rehabilitation and treatment of disturbed lands, Sixth Billings Symposium, March 21-27, 1993, Reclamation Research Unit Publication No. 9301*, p. 176-186.
- Prusty, B.G., Sahu, K.C., and Godgul, Geeta, 1994, Metal contamination due to mining and milling activities at the Zwar zinc mine, Rajasthan, India I. Contamination of stream sediments: *Chemical Geology*, v. 112, p. 275-291.
- Runnells, D.D., Shepherd, T.A., and Angino, E.E., 1992, Metals in water--determining natural background concentrations in mineralized areas: *Environmental Science Technology*, v. 26, p. 2316-2323.
- Ryall, W.R., 1981, The forms of mercury in some Australian stratiform Pb-Zn-Ag deposits of different regional metamorphic grades: *Mineral Deposita*, v. 16, p. 425-435.
- Sahu, K.C., Prusty, B.G., and Godgul, Geeta, 1994, Metal contamination due to mining and milling activities at the Zwar zinc mine, Rajasthan, India II. Dispersion in floodplain soils: *Chemical Geology*, v. 112, p. 293-307.
- Sangster, D.F., ed., 1983, *Sediment-hosted stratiform lead-zinc deposits: Mineralogical Association of Canada Short Course Handbook*, v. 8, 309 p.
- _____. 1990, Mississippi Valley-type and sedex lead-zinc deposits--a comparative examination: *Transactions of the Institution of Mining and Metallurgy*, section B, v. 99, p. B21-B42.
- Schmidt, J.M., in press, Shale-hosted Zn-Pb-Ag and barite deposits of Alaska, in Goldfarb, R.J., and Miller, L., eds., *Mineral deposits of Alaska: Economic Geology Monograph*.
- Taylor, G.F., 1984, Gossan profiles developed above stratabound sulfide mineralization: *Journal of Geochemical Exploration*, v. 22, p. 351-352.
- Taylor, G.F., Wilmschurst, J.R., Togashi, Y., and Andrew, A.S., 1984, Geochemical and mineralogical halos about the Elura Zn-Pb-Ag orebody, western New South Wales: *Journal of Geochemical Exploration*, v. 22, p. 265-290.
- Theobald, P.K., Barton, H.N., Billings, T.M., Frisken, J.G., Turner, R.L., and VanTrump, G., Jr., 1978, Geochemical distribution of elements in stream sediment and heavy-mineral concentrate samples in the southern half of the National Petroleum Reserve, Alaska: U.S. Geological Survey Open-File Report 78-517, scale 1:500,000.
- Turner, R.J.W., and Einaudi, M.T., 1986, The genesis of stratiform sediment-hosted lead and zinc deposits: *Conference Proceedings: Stanford University Publications in the Earth Sciences Volume XX*, 222 p.
- U.S. Bureau of Mines, 1993, *Minerals Yearbook*.
- Vine, J.D., and Tourtelot, E.B., 1970, *Geochemistry of black shales--a summary report: Economic Geology*, v. 65, p. 253-272.
- Young, L.E., 1989, Geology and genesis of the Red Dog deposit, western Brooks Range, Alaska: *Canadian Institute of Mining and Metallurgy Bulletin*, v. 82, no. 929, p. 57-67.

MISSISSIPPI VALLEY-TYPE PB-ZN DEPOSITS (MODELS 32a, b; Briskey, 1986a,b)

by David L. Leach, John B. Viets, Nora Foley-Ayuso, and Douglas P. Klein

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Mississippi Valley-type (MVT) lead-zinc deposits are a varied family of epigenetic ore deposits that form predominantly in dolostone and in which lead and zinc are the major commodities. Most are found in rocks of Cambrian and Ordovician, Devonian and Carboniferous, and Triassic ages. Undeformed orogenic foreland carbonate platforms are the favored tectonic setting for MVT deposits; some are in carbonate sequences in foreland thrust belts bordering foredeeps and fewer still are associated with rift zones.

MVT deposits typically are in districts covering hundreds, or even thousands, of square kilometers. Within each district, deposits display remarkably similar features, including mineral assemblages, isotopic compositions, and textures. Ore controls typically are district-specific; examples include shale edges (depositional margins of shale units), limestone-dolostone transitions, reef complexes, solution collapse breccias, faults, and basement topography. Most MVT ore districts are the product of regional or sub-continental scale hydrological processes. Therefore, diversity among MVT districts is expected because of wide ranging fluid compositions, geological and geochemical conditions, fluid pathways, and precipitation mechanisms possible at the scale of MVT fluid migration.

Deposit geology

The most important characteristics of MVT lead-zinc deposits (Leach and Sangster, 1993) are: (1) most deposits are in dolostone, less commonly in limestone or sandstone, (2) ore is epigenetic and stratabound, (3) deposits are not associated with igneous activity, (4) deposits are at shallow depths at flanks of basins, (5) deposits are in platform carbonate sequences, located either in relatively undeformed rocks bordering foredeeps or in foreland thrust belts, (6) most deposits are in districts that cover hundreds of square kilometers; a number of districts may even form metallogenic provinces, (7) deposits form districts that are localized by geologic features, including breccias, depositional margins of shale units (shale edges), facies tracts, faults, and basement highs that permit upward migration of ore fluids, (8) ore deposition temperatures are low (50°C to 200°C), but typically higher than those attributable to local basement-controlled thermal gradients; districts are commonly in thermal equilibrium with respect to surrounding host rocks, (9) deposits are mineralogically simple; dominant minerals are sphalerite, galena, pyrite, marcasite, dolomite, calcite, and quartz, (10) associated alteration consists mainly of dolomitization, brecciation, host-rock dissolution, and dissolution/crystallization of feldspar and clay, (11) evidence of carbonate host rock dissolution, expressed as slumping, collapse, brecciation, or some combination of these, is common, (12) ore fluids were dense basinal brines, typically containing 10 to 30 weight percent salts, (13) isotopic data indicate crustal sources for both metal and reduced sulfur, (14) sulfide mineral textures are extremely varied; ore ranges from coarsely crystalline to fine-grained, massive to disseminated.

Examples

MVT deposits are found throughout the world (fig. 1); the largest and most intensely studied are in North America. Important North American districts include the Viburnum Trend and the Old Lead Belt (Southeast Missouri Lead district), Tri-State, Upper Mississippi Valley, Central Tennessee, East Tennessee (Mascot-Jefferson and Copper Ridge subdistricts), Austinville-Ivanhoe, Pine Point, Nanisivik, Polaris, Daniel's Harbour, and Gays River. Active MVT deposits in the United States are in the Viburnum Trend (southeast Mo.), Central Tennessee, and East Tennessee districts.

Spatially and (or) genetically related deposit types

Deposit types (Cox and Singer, 1986) associated with MVT deposits are believed to be part of a spectrum of sediment-hosted ore deposits (Sangster and Leach, 1995) that includes sedimentary exhalative lead-zinc-barite deposits (Model 31a), carbonate-hosted fluorite deposits (for example, Illinois-Kentucky fluorite deposits), carbonate-platform deposits (for example, Mt. Isa and HYC, Australia; Balmat-Edwards, N.Y.), Kipushi copper deposits (Model 32c), and sandstone-lead deposits (Model 30a) (for example, Laisvall, Sweden; Largentiere, France).

Potential environmental considerations

Environmental concerns associated with mining MVT deposits are largely unrecognized due to the common assumption



Figure 1. Location of MVT deposits and districts throughout the World: 1, Polaris; 2, Eclipse; 3, Nanisivik; 4, Gayna; 5, Bear-Twit; 6, Godlin; 7, Pine Point district; 8, Lake Monte; 9, Nancy Island; 10, Ruby Lake; 11, Robb Lake; 12, Monarch-Kicking Horse; 13, Giant; 14, Silver Basin; 15, Gays River; 16, Daniels Harbour; 17, Metaline district; 18, Upper Mississippi Valley district; 19, southeast Missouri district (Old Lead Belt, Viburnum Trend, Indian Creek); 20, central Missouri district; 21, Tri-State district; 22, northern Arkansas district; 23, Austinville; 24, Friedensville; 25, central Tennessee district; 26, east Tennessee district; 27, San Vicente; 28, Vazante; 29, Harberton Bridge; 30, Silesian district; 31, Alpine district; 32, Pering; 33, Sorby Hills; 34, Coxco; 35-37, Lennard Shelf district (Cadjebut, Blendvale, Twelve Mile Bore); 38, El-Abad-Mekta district. Adapted from Sangster (1990).

that the acid-buffering potential of typical carbonate host rocks controls the mobility of zinc, cadmium, iron, lead, and other metals. However, the influence of alteration halos, regional aquifers and karst, variable iron sulfide mineral content, climatic influences, and the presence of various trace elements in ore have not been adequately evaluated. Surface disturbance: MVT deposits characteristically are in districts that are distributed over hundreds of square kilometers. The widespread distribution of MVT deposits within a region requires a regional approach to environmental studies. The Southeast Missouri lead district covers more than 2,500 square kilometers, the Tri-State district is at least 1,800 square kilometers, the Pine Point district is more than 1,600 square kilometers, the East Alpine district is about 10,000 square kilometers, and the Upper Mississippi Valley district is about 7,800 square kilometers. Numerous open pits are present within some districts, especially in abandoned districts such as the Tri-State district, Okla., Mo., and Kans. Modern mining techniques return most waste rock to underground workings; surface tailings and mineral processing facilities pose the most serious environmental concerns.

Water quality: Because ore is dominantly carbonate-rock hosted, local rock buffers potential acid mine and tailings water. Therefore, significant mobility of heavy metals is likely to be spatially restricted. In some districts, water from underground MVT mines serves as a local domestic water source (for example, Viburnum, Mo. and Upper Silesia, Poland). Most MVT deposits are in carbonate aquifers that can have enormous fluid transmissivity of regional extent. Many ore districts contain one or more sandstone aquifers that potentially allow greater contaminant dispersion than carbonate aquifers. Low iron oxide and clay contents of carbonate aquifers could permit greater dispersion of some elements at neutral or slightly alkaline pH.

Mineral processing: Tailings ponds and smelter activities generally pose the greatest environmental concerns. Significant amounts of airborne lead, arsenic, cadmium, and other elements are known to be significant sources of

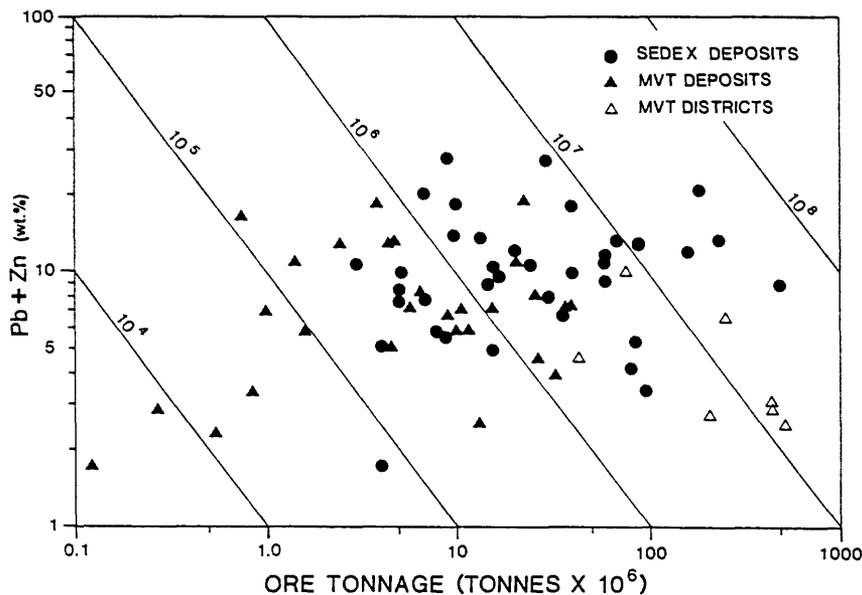


Figure 2. Grade-tonnage for MVT deposits and districts and for sedimentary exhalative deposits. Diagonal lines represent total tonnage of contained lead and zinc (adapted from Sangster, 1990).

metal contamination in many districts. In Upper Silesia, for example, soil in the vicinity of smelters contains thousands of ppm lead (Dudka and others, 1995).

Exploration geophysics

Geophysical exploration has been used successfully in some districts to map known geologic ore controls (Guinness and others, 1983). For example, airborne magnetic surveys have been used in Southeast Missouri to define buried Precambrian topography, an important control on the localization of some ore (Allingham, 1966; Cordell, 1979; Cordell and Knepper, 1987). Galena and pyrite are consistently conductive and have associated induced polarization anomalies, whereas sphalerite's resistivity is variable (Sumner, 1976). In Ireland, induced polarization and geochemical surveys have been combined to make discoveries of carbonate-hosted sulfide deposits (Hallov, 1966); associated resistivity data have also been used to map subsurface faults that control mineralization and to map mineralized carbonate reefs (Hallov, 1966; Hitzman and others, 1992).

References

General geology: Heyl and others (1959), a series of papers in Brown (1967), Anderson and Macqueen (1982), Kisvarsanyi and others (1983), Briskey (1986a,b), Sverjensky (1986), Leach and Sangster (1993), Leach (1994), and Sangster and Leach (1995).
 Environmental geology: Smith and Schumacher (1991) and Dudka and others (1995).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

In Figure 2, data for deposits versus districts are identified by different symbols. District totals for metals may represent several dozen individual deposits; for example, the Pine Point and Upper Mississippi Valley districts contain more than 80 and nearly 400 deposits, respectively.

Individual deposits are generally small; most yield less than ten million tons of ore. An analysis of the Pine Point district, for example, showed that most deposits contained between 0.2 and 2 million tons of ore, and the largest had nearly 18 million tons (Sangster, 1990). For the Upper Mississippi Valley district, Heyl and others (1959) reported that the average deposit size was between 0.1 and 0.5 million tons, although a few contained as much as 3 million tons of ore.

Combined lead plus zinc grades in MVT deposits (districts) seldom exceed 10 percent. The Polaris deposit, in the Canadian Arctic Archipelago, is not only unusually large (22 million tonnes), but is anomalously high grade as well (18 percent lead plus zinc). A majority (about 85 percent) of deposits (districts) are zinc-rich relative to lead and have Zn/(Zn+Pb) values between 0.5 and 1.0, with a distinct mode at 0.8. A smaller group, consisting of the entire Southeast Missouri district plus a few other small deposits, has a modal value of about 0.05 and is distinctly

anomalous in this regard.

Host rocks

Most MVT deposits are hosted by dolostone; less important hosts are limestone and sandstone.

Surrounding geologic terrane

MVT deposits commonly are at shallow depths along basin flanks. They form in platform carbonate sequences, located either in relatively undeformed rocks bordering foredeeps or in foreland thrust belts. Some deposits are associated with salt diapirs (for example, Bou Grine in Tunisia). Most deposits are surrounded by carbonate rocks with high acid buffering capacity.

Wall-rock alteration

Dissolution, recrystallization, and hydrothermal brecciation of host carbonate rocks within and peripheral to mineralized rock is common to virtually all MVT deposits. These effects may develop in conjunction with silicification and dolomitization and constitute the major form of wall-rock alteration in MVT districts. Ore-related silicification of host rocks limits the buffering capacity of rocks near ore deposits and therefore influences the extent of metal-bearing water dispersion in some districts (for example, Tri-State). Hydrothermal dolomite may be pre-, syn-, or post-ore and has commonly replaced pre-ore carbonate host rocks to form distinctive alteration halos around deposits (for example, the East Tennessee and Tri-State districts). Formation of authigenic clay and feldspar minerals and destruction of detrital potassium-silicate minerals are recognized in some districts.

Nature of ore

MVT ore is extremely varied in character and form. Orebodies range from massive replacement zones to open space fillings of fractures and breccias to disseminated clusters of crystals that occupy intergranular pore space. Crystal size ranges to as much as a meter or more in some "crystal caverns" in the Tri-State and Central Tennessee districts. In some districts, notably Pine Point, Silesia, Polaris, and Cadjebut, much of the ore forms extremely fine-grained, laminated aggregates of botryoidal (colloform) sphalerite, commonly with intergrown dendritic or skeletal galena. Most MVT deposits show clear evidence that open space deposition was accompanied by dissolution and replacement of host carbonate rocks. Carbonate host rock replacement is, in some cases, nearly complete, as in the massive sulfide zones at Nanisivik and Polaris. Ore-hosting structures are most commonly zones of highly brecciated dolomite; in some instances (for example, Pine Point and Daniels Harbour) these zones are arranged in linear patterns suggesting a tectonic control, although faults of large displacement are never present. In some districts, notably Upper Silesia and Ireland, faults, which reflect reactivated basement structures, are the most important ore control.

Deposit trace element geochemistry

Trace and minor element suites and abundances vary between districts; the trace element content of minerals from different paragenetic stages within a district often display significant variation. Table 1 summarizes metal abundances characteristic of some North American MVT districts. Arsenic, thallium, and cadmium contents of sphalerite from different MVT districts are compared in figure 3.

Ore and gangue mineralogy and zonation

Most MVT deposits have simple mineral assemblages that consist of galena, sphalerite, pyrite, and marcasite. The most important environmental consideration for MVT deposits may be their iron sulfide content. The abundance of iron sulfide minerals relative to that of other sulfide minerals in MVT deposits ranges from nil to dominant. Iron sulfide abundances vary not only between districts but among mines within single districts. The Appalachian districts contain trace to minor amounts of iron sulfide, whereas the sulfide mineral assemblage at Nanisivik is dominantly iron sulfide. MVT deposits in the Viburnum Trend contain from a few tenths percent to several percent iron sulfide minerals. Trace element abundances in iron sulfide minerals are often highly variable in different parts of a given mineral paragenesis. Chalcopyrite, bornite, and other copper sulfide minerals are abundant in some districts. Although most districts are characterized by rather simple mineral assemblages, Viburnum Trend ore contains a minor but complex suite of minerals that includes siegenite, bornite, tennantite, bravoite, digenite, covellite, arsenopyrite, fletcherite, adularia, pyrrhotite, magnetite, millerite, polydymite, vaesite, djurleite, chalcocite, anilite, and enargite. Some of these minor phases are present in trace amounts in many MVT districts.

With the exception of the Southeast Missouri district, all major MVT districts are zinc-rich relative to lead

Table 1. Geochemical characteristics of selected North American MVT Deposits.

District	Major	Minor	Trace
Viburnum Trend	Pb Zn Fe	Cu Co Ni	Cd Ag In Ge Ga Sb Bi As Mo Sn Au (1)
Old Lead Belt	Pb Zn Fe	Cu Ni Co	Cd Ag In Ge Ga Sb Bi As Mo Sn Au (1)
Central Missouri	Ba Zn Pb	Fe	Cd Cu
Northern Arkansas	Zn	Pb Fe	Cd Cu Ag Ge Ga In Bi As (1)
Tri-State	Zn Pb	Fe Cu	Cd Ba Cu Ag Ge Ga Co Ni In Sb Bi (1)
Upper Mississippi Valley	Zn Pb Fe	Cu Ba	Cd Ag Ge Ga Co Ni In (2)
Central Tennessee	Zn	Pb Fe F Ba	Cd Cu Ag Ge Ga Co Ni Hg As (1)
East Tennessee	Zn	Pb Fe	Cd Cu Ag Ge Ga (1)
Austinville	Zn Pb Fe	Cu	Cd Ge Ga F Ba (1)
Friedensville	Zn	Pb	Cd
Timberville	Zn Fe	Pb Cd	
Gays River	Zn Pb Fe	Cu Ba	F
Newfoundland Zinc	Zn	Pb Fe	Cd
Polaris	Zn Pb Fe		
Nanisivik	Zn Pb Fe		Ba Ag (3)
Pine Point	Zn Pb Fe		Cd Ag As Ni (3)
Gayna River	Zn Pb Fe	Ba F	

Ba, in barite; F, in fluorite.

The distinction between major and minor chemical characteristic is subjective because seldom are grades for minor metals published and there is an inherent high variability in minor metals even between deposits within a single district; typically the minor components are less than 1 percent but greater than 0.1 percent. Trace elements are a tabulation of elements detected in various mineral phases by a variety of techniques; therefore, they may be used as general guides for the deposits. Trace elements in bold type may be useful geochemical pathfinders. Trace element data from (1) Hagni (1983), (2) Heyl and others (1959), (3) Sangster (1968), and unpublished data.

and have Zn/(Zn+Pb) ratios greater than 0.5; this ratio is less than 0.1 in Southeast Missouri deposits. Some ore deposits, including many in the East Tennessee and Daniels Harbour districts, are essentially lead-free and have Zn/(Zn+Pb) ratios approaching 1.0. Although the Appalachian MVT deposits are generally galena poor, some contain significant amounts of galena (for example, Austinville, Va.).

Because most MVT deposits are mineralogically simple, mineralogic zonation has been described for only a few areas (Southeast Missouri, Pine Point, and Upper Mississippi Valley). Lead, zinc, iron, copper, nickel, and cobalt abundances are zoned in mineralogically complex deposits of the Southeast Missouri district (Grundmann, 1977; Rogers and Davis, 1977; Sweeney and others, 1977; Hagni, 1983; Mavrogenes and others, 1992). In the Upper Mississippi Valley district, a local zinc-copper belt is flanked by barite, whereas lead is widespread (Heyl and others, 1959). At Pine Point, Fe/(Fe+Zn+Pb) increases and Pb/(Pb+Zn) decreases outward from prismatic orebodies (Kyle, 1981).

The most abundant gangue mineral is hydrothermal dolomite, which may form alteration halos around MVT ore deposits (for example, northern Arkansas, East Tennessee, and Tri-State). Barite and fluorite are abundant gangue minerals in some districts. Other common gangue minerals include calcite and quartz.

Mineral characteristics

Sulfide mineral textures are extremely varied; ore ranges from coarsely crystalline to fine-grained, massive to disseminated.

Secondary mineralogy

Secondary minerals consist of smithsonite (the dominant ore mineral in some districts prior to the 1950s), calamine, anglesite, cerussite, malachite, sulfur, goslarite, epsomite, gypsum, melanterite, szomolnokite, copiatite, carphosiderite, diadochite, hydrous iron oxide minerals, hematite, greenockite.

Topography, physiography

Most MVT deposits are located in flat-lying carbonate sequences. However, some deposits are located in thrust and fold belts (for example, Monarch-Kicking Horse, British Columbia; Alpine district in Europe).

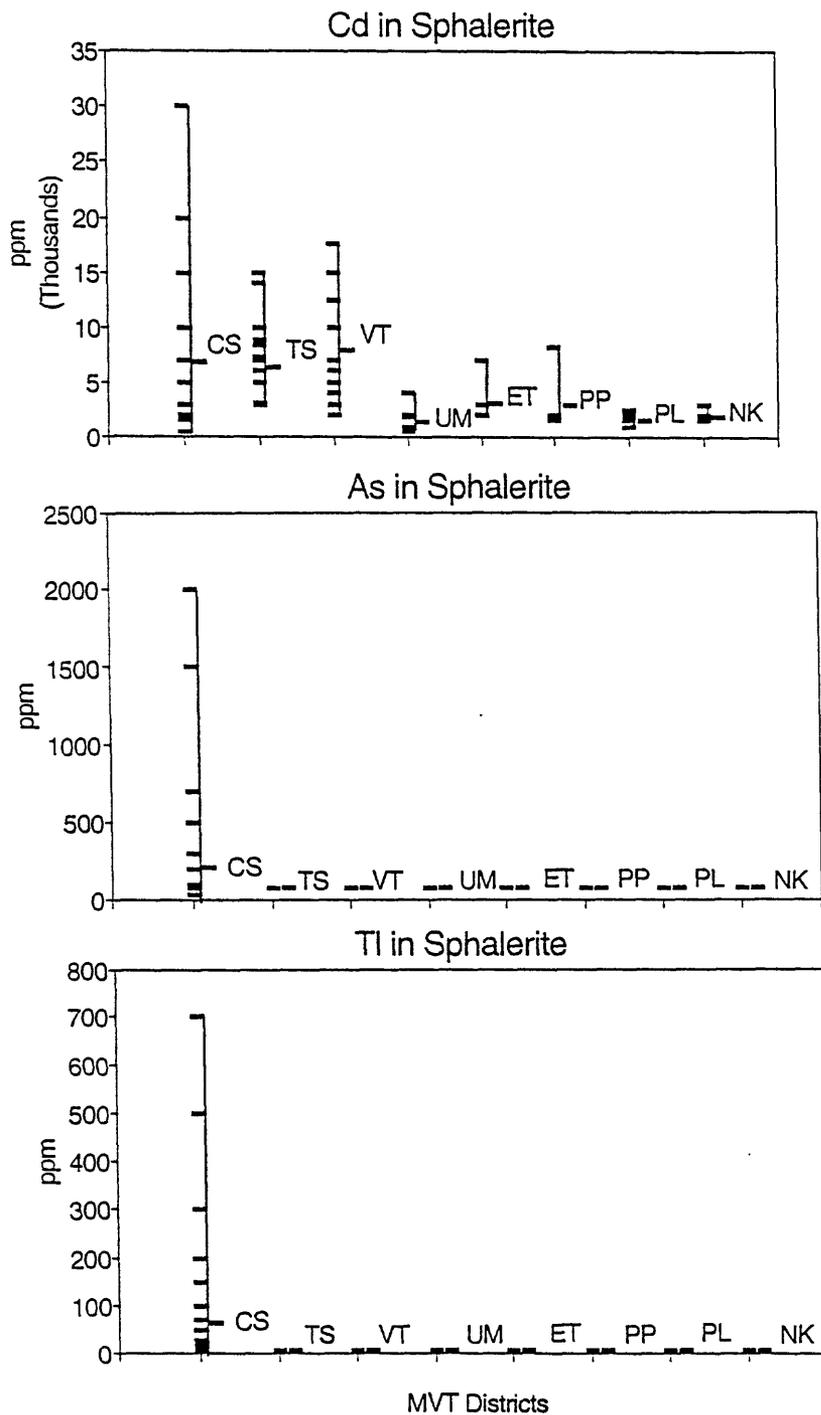


Figure 3. Range of concentrations and mean values, in parts per million, for cadmium, arsenic, and thallium in sphalerite from major Mississippi Valley districts: CS, Cracow-Silesia; TS, Tri-State; VT, Viburnum Trend; UM, Upper Mississippi Valley; ET, East Tennessee; PP, Pine Point; PL, Polaris; NK, Nanisivik (from Viets and others, in press).

Hydrology

The formation of MVT deposits requires enormous quantities of fluid; therefore, most districts have some spatial connection to major aquifers, karst systems, and faulted ground with high fluid transmissivity. However, present hydrology can be quite different from paleohydrology. Few generalizations on present hydrological environments are possible for MVT districts of the World; permafrost conditions prevail at the Polaris mine, whereas Saharan conditions prevail around North Africa deposits.

Mining and milling methods

Present mining is generally by underground room-and-pillar or by longwall methods. Ore is processed by pulverizing and flotation, concentrates are now generally shipped to smelters outside mining districts.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Ground water: Water from a depleted part of one mine in the Viburnum Trend is used as the municipal water supply for Viburnum, Mo. This water meets all U.S. Environmental Protection Agency water quality standards with the exception of that for sulfate (Missouri Department of Natural Resources, 1991). Reported sulfate content is 436 mg/l, whereas the accepted water quality standard is 250 mg/l. Other parameters are pH=7; alkalinity=260; 0.18 mg/l iron; 5.7 mg/l sodium; 72 mg/l magnesium; 0.24 mg/l fluorine; 856 mg/l total dissolved solids; and lead, zinc, and cadmium abundances are in the $\mu\text{g/l}$ range. In addition, several communities in Upper Silesia, Poland, use water from underground lead-zinc mines as their only domestic water supply. The sulfate content of this water is variable but is commonly in the 400 to 800 mg/l range and lead is present in the $\mu\text{g/l}$ range.

Surface water: The Big River flows through the Old Lead Belt and near many waste piles. Water quality data (Smith and Schumacher, 1991) for a site about 15 km above mining and smelting activity reflect background water parameters: $\text{SO}_4 < 24$ mg/l, lead < 10 $\mu\text{g/l}$, cadmium < 2 $\mu\text{g/l}$, and zinc < 27 $\mu\text{g/l}$. During its flow through the district, carbonate buffering causes water pH (6.6-8.5) to be virtually unchanged. However, SO_4 , lead, and zinc abundances increase due to inputs primarily from surface mine wastes. At a site 5 km below the district, the water contains 40-140 mg/l SO_4 , 10 $\mu\text{g/l}$ lead, < 1 $\mu\text{g/l}$ cadmium, and 110-160 $\mu\text{g/l}$ zinc.

Metal mobility from solid mine wastes

Metal mobility away from MVT deposits is limited by the abundance of carbonate rock associated with these deposits; carbonate rock consumes acid mine drainage and inhibits aqueous metal mobility. Heavy metals abundances were determined at four seepage sites related to mine wastes in the Old Lead Belt (Smith and Schumacher, 1991). Maximum concentrations measured were: 850 mg/l SO_4 , less than 10 $\mu\text{g/l}$ copper, 80 $\mu\text{g/l}$ lead, 18,000 $\mu\text{g/l}$ zinc, and 28 $\mu\text{g/l}$ cadmium. During two years of monitoring at the four sites, pH of the seeps ranged from 6.23 to 8.61. A lead-zinc ratio of 5 for Old Lead Belt ore (Snyder and Gerdman, 1968) indicates that zinc is clearly more mobile than lead or cadmium in water leaching waste materials; these relative mobilities also appear to apply to Big River water.

Soil sediment signatures prior to mining

In the region of the East Tennessee district, readily detectable zinc, iron, and locally lead anomalies are found in residual soil and stream sediment. For example, NURE data for stream sediment indicate that over 100 samples from the Bluefield 1°x2° quadrangle (Va., W. Va., Tenn., and N.C.) have anomalous lead and zinc abundances (> 20 ppm zinc and > 10 ppm lead) that may be attributable to lead and zinc deposits in the region. Proctor and others (1981) conducted a survey of the acid soluble lead content of 416 stream sediment samples collected from active streams throughout a 7,000 square mile area that includes much of the Southeast Missouri lead district. Samples from areas underlain by Paleozoic carbonate rock and considered to be largely non-mineralized have a mean lead content of 25 ppm, whereas samples from areas of active mining and milling contain an average of 393 ppm lead. The specific residence of lead was not identified but Proctor and others (1981) considered metal from insoluble rock residues, primary dispersion halos, secondary dispersion of primary mineralization, and recent dispersion due to mining and milling and smelting activities as possible lead sources.

Most MVT deposits have essentially no geochemical signature because of limited primary dispersion of ore related elements into the surrounding carbonate rocks (Lavery and others, 1994). However, in some districts where ore-bearing zones have been weathered, soil contains anomalous concentrations of lead and zinc. Soil geochemistry in the Irish district (Hitzman and others, 1992) and in the Newfoundland zinc district (Davenport and others, 1975) are effectively used in exploration.

Although MVT deposits are hosted by carbonate rocks, residual soil overlying some deposits can be acidic; it can have moderate to high permeability, medium to high erosion potential, and moderate to high water capacity. These factors can influence the mobility of metals into the environment.

In the area of the Austinville-Ivanhoe, Va., district background carbonate rocks typically contain about 20 ppm zinc and 9 ppm lead. However, extensive volumes of rock containing dolomite cement are widely peripheral to mineralized zones (for example, Wythe County, Va.; Barnaby, 1989); replacement dolomite and late calcite have considerably elevated abundances of some trace metals, including as much as 9,300 ppm iron, 200 ppm strontium,

1,500 ppm lead, 1,000 ppm manganese, and 10,000 ppm zinc.

Potential environmental concerns associated with mineral processing

Most modern underground carbonate hosted zinc-lead mining operations return a significant amount of mine waste and mill tailings to underground workings as fill. In the case of the Polaris mine in the Canadian Arctic, waste slurries are used to fill mining voids in their modified room and long pillar galleries. Once frozen, waste supports the roof and long pillars are mined so that essentially the entire deposit is mined. In Upper Silesia, Poland, surface disposal of iron sulfide-mineral-rich-tailings presents a potentially serious environmental problem in the district.

Surface mill tailings pose the major potential environmental concern associated with MVT deposits. Although modern processing facilities carefully monitor water draining from processing sites, some water, with elevated concentrations of lead, zinc, cadmium, arsenic, thallium, and a variety of trace elements characteristic of the ore deposit, may escape. Airborne dust from tailing ponds can potentially contribute ore particulates.

Smelter signatures

Studies of the effects of airborne smelter effluent in the Viburnum Trend of southeast Missouri by Bornstein and Bolter (1991) indicate that soil pH at distances of as much as 6.4 km from the smelter source and as deep as 15 cm are significantly reduced, ranging from 4.4 at 15 cm to 5.1 at 5 cm depths. At 9.6 km, pH ranged from 6.8 to 7.0. The sulfur content of the soil correlates with the pattern of pH depletion. Lead, zinc, copper, cadmium, cobalt and nickel contents of leaf litter and underlying soil decrease with distance from the point source and depth below surface. The extent of heavy metal enrichment was about half that of the area affected by sulfur enrichment suggesting that SO₂ is the principal sulfur species.

Palmer and Kucera (1980) conducted a similar study for lead, by sampling both sycamore leaves and twigs and soil, around four smelter sites in southeast Missouri. Their results were very similar to those of Bornstein and Bolter (1991) and indicate that dominant wind directions and degree of lead enrichment are correlated.

Climate effects on environmental signatures

Climate is extremely critical in assessing the environmental concerns associated with this deposit type. Potential acid-mine drainage problems related to MVT deposits in relatively dry climate settings are much less than those of deposits in warm, wet climates. Acid-rain aggravates potential environmental problems in the mid-Atlantic and northeastern United States, especially the Appalachians. Small MVT deposits are present throughout the Appalachians in Cambrian to Mississippian carbonate rock sequences (for example, Shady Dolomite and Knox Dolomite).

The Austinville-Ivanhoe, Va., deposit is a prime example of how climatic conditions and soil properties interact to increase potential environmental problems. For example, in Wythe County, Va., soil is moderately to very strongly acidic (pH 5.6 to <4.5) although as much as 30 percent of the surface may consist of dolomitic limestone outcrops; the soil has moderate permeability, medium to high erosion potential, and moderate water capacity. Much of the soil is deemed suitable for cultivated crops (legumes), hay, or pasture and much is prime farmland (corn, vegetables, small grain, and strawberries) (U.S. Department of Agriculture, 1992). Most of the area is in the drainage basin of the New River, which has water quality problems including excessive concentrations of trace metals such as zinc, copper, lead, iron, and locally acidification caused by mining activities (Virginia Water Control Board, 1990a,b). Prime farmlands of the valley and ridges within and adjacent to the Appalachian Mountains (near historic lead and zinc mines) may be affected by metal contamination resulting from past (and future) releases of lead and zinc into soil and ground water as a result of environmental conditions specific to the region.

In contrast to the Appalachian deposits, the Polaris deposit is in a region of permafrost with little opportunity for dispersion into the environment from surface or ground water. Likewise, deposits in arid regions such as Bou Grine in Tunisia, have little opportunity for metal mobility in water.

Geoenvironmental geophysics

In environmental and remediation studies, electrical, seismic surveys, and ground penetrating radar (for sources within meters of the surface) can help identify shallow mine shaft locations and map geologic structure within and beneath tailings. Induced polarization and resistivity surveys can be used to identify the source and extent of acid drainage. Seismic surveys can help distinguish sandstone aquifers from carbonate rocks. However, freshwater sandstone aquifers in dominantly carbonate rock, are associated with minor resistivity contrasts unless the water contains elevated abundances of dissolved metals.

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REFERENCES CITED

- Allingham, J.W., 1966, Aeromagnetic anomalies in the Bonne Terre area of the southeast Missouri Mining District: *Mining Geophysics*, v. 1, Society Exploration Geophysics, p. 36-53.
- Anderson, G.M. and Macqueen, R.W., 1982, Ore deposit models-6. Mississippi Valley-type lead-zinc deposits: *Geoscience Canada*, v. 9, p. 107-117.
- Barnaby, R.J., 1989, Sedimentology and diagenesis of Lower to Middle Cambrian carbonate platform: Blacksburg, Virginia Polytechnic Institute and State University, Ph.D. dissertation, 204 p.
- Briskey, J.A., 1986a, Descriptive model of southeast Missouri Pb-Zn, in Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 220-221.
- _____ 1986b, Descriptive model of Appalachian Zn, in Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 222-223.
- Bornstein, R.E. and Bolter, E., 1991, Long-term effects of lead smelting in soils, in Beck, B.D., ed., *Trace substances in environmental health XXV*, Gradient Corporation, Cambridge, Mass., United-States: *Trace Substances in Environmental Health*, v. 25, p. 71-83.
- Brown, J.S., 1967, Genesis of stratiform lead-zinc-barite-fluorite deposits: Monograph 3, Economic Geology Publishing Company, Lancaster, Pennsylvania, 443 p.
- Cordell, L., 1979, Gravity and aeromagnetic anomalies over basement structure in the Rolla quadrangle and the southeast Missouri lead district: *Economic Geology*, v. 74, p. 1383-1394.
- Cordell, Lindrith, and Knepper, D.H., 1987, Aeromagnetic images: fresh insight to the buried basement, Rolla quadrangle, southeast Missouri: *Geophysics*, v. 52, no. 2, p. 218-213.
- Cox, D.P., and Singer, D.A., 1986, *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, 379 p.
- Davenport, P.H., Hornbrook, E.H.W., and Butler, A.J., 1975, Regional lake sediment geochemical survey for zinc mineralization in western Newfoundland: *Developments in Economic Geology*, no. 1 (Geochemical exploration 1974), p. 555-578.
- Dudka, S., Piotrowska, A., and Witek, T., 1995, Trace metal contamination of soils and crop plants by the mining and smelters in Upper Silesia, Southern Poland: *Journal of Exploration Geochemistry*, v. 52, p. 237-250.
- Grundmann, Jr., W.H., 1977, Geology of the Viburnum No. 27 Mine, Viburnum Trend, Southeast Missouri: *Economic Geology*, v. 72, p. 349-364.
- Guinness, E.A., Arvidson, R.E., Leff, C.E., Edwards, M.H., Bindschadler, D.L., 1983, Digital image processing applied to analysis of geophysical and geochemical data for southern Missouri: *Economic Geology*, v. 78, p. 654-663
- Hagni, R.D., 1983, Minor elements in Mississippi Valley-type ore deposits, in Shanks, W.C., ed., *Cameron Volume on Unconventional Mineral Deposits*, Society of Economic Geology and Society of Mining Engineers, AIME, New York, p. 44-88.
- Hallof, P.G., 1966, The use of resistivity results to outline sedimentary rock types in Ireland: *Mining Geophysics*, v. 2, Society of Exploration Geophysics, p. 18-27.
- Heyl, A.V., Agnew, A.F., Lyons, E.J. and Behre, C.H., 1959, The geology of the Upper Mississippi Valley zinc-lead district: *U.S. Geological Survey Professional Paper 309*, 310 p.
- Hitzman, M.W., O'Connor, P.O., Shearley, E., Schaffalitzky, C., Beaty, D.W., Allan, J.R., and Thompson, T., 1992, Discovery and geology of the Lisheen Zn-Pb-Ag prospect, Rathdowney Trend, Ireland, in Bowden, A., Earls, G., O'Connor, P.G., and Pyne, J.F., *The Irish Minerals Industry 1980-1990: Irish Association of Economic Geology*, Dublin, Ireland, p. 227-246.
- Kisvarsanyi, G., Grant, S.K., Pratt, W.P. and Koenig, J.W., eds., 1983, *Proceedings of International Conference on Mississippi Valley Type Lead-Zinc Deposits: Rolla*, University of Missouri, 603 p.
- Kyle, J.R., 1981, Geology of the Pine Point lead-zinc district, in Wolf, K.H., ed., *Handbook of strata-bound and stratiform ore deposits: Elsevier Publishing Company, New York*, v. 9, p. 643-741.
- Lavery, N.G., Leach, D.L., and Saunders, J.A., 1994, Litho-geochemical investigations applied to exploration for sediment-hosted Zn-Pb ore deposits, in Fontebote, L. and Boni, M., eds., *Sediment Hosted Zn-Pb Ores*, Springer-Verlag, p. 393-428.

- Leach, D.L., 1994, Genesis of the Ozark Mississippi Valley-type metallogenic province, *in* Fontebote, L. and Boni, M., eds., *Sediment Hosted Zn-Pb Ores*, Springer-Verlag, p.104-138.
- Leach, D.L. and Sangster, D.F., 1993, Mississippi Valley-type lead-zinc deposits, *in* Kirkham, R.V., Sinclair, W.D., Thorp, R.I., and Duke, J.M., eds., *Mineral Deposit Modeling*, Geological Association of Canada Special Paper 40, p. 289-314.
- Mavrogenes, J.A., Hagni, R.D. and Dingess, P.R., 1992, Mineralogy, paragenesis, and mineral zoning of the West Fork mine, Viburnum Trend, Southeast Missouri: *Economic Geology*, v. 87, p. 113-124.
- Missouri Department of Natural Resources, 1991, *Census of Missouri Public Water Systems*, Missouri Department of Natural Resources, Division of Environmental Quality, 460 p.
- Palmer, K.T. and Kucera, C.L., 1980, Lead contamination of sycamore and soil from lead mining and smelting operations in eastern Missouri: *Journal of Environmental Quality*, v. 9, p. 106-110.
- Proctor, P.D., Afzali, B., Collins, S., Panhorst, T., and Sinha, B., 1981, Lead additions to stream sediments, Southeast Missouri: [abst] *Abstracts with Programs*, Geological Society of America, v. 13, No. 5, p. 261.
- Rogers, R.K. and Davis, J.H., 1977, Geology of the Buick Mine, Viburnum Trend, Southeast Missouri: *Economic Geology*, v. 72, p. 372-380.
- Sangster, D.F., 1968, Some chemical features of lead-zinc deposits in carbonate rocks: *Canada Geological Survey Paper 68-39*, 17 p.
- _____ 1990, Mississippi Valley-type and sedex deposits: a comparative examination: *Transactions of the Institution of Mining and Metallurgy, Section B*, v. 99, p. B21-B42.
- Sangster, D. and Leach, D.L., 1995, Evidence for a genetic link between SEDEX and MVT deposits, *in* Leach, D.L. and Goldhaber, M.B., eds., *Extended Abstracts, International Field Conference on Carbonate-hosted Lead-Zinc deposits*, St. Louis Missouri, June 1-4, p. 260-263.
- Smith, B.J. and Schumacher, J.G., 1991, Hydrochemical and sediment data for the Old Lead Belt, southeastern Missouri, 1988-89: *U.S. Geological Survey Open File Report 91-0211*, 98 p.
- Snyder, F.G., and Gerdemann, P.E., 1968, Geology of the southeast Missouri lead district, *in* Ridge, J.D., ed., *Ore deposits of the United States, 1933-1967 (Graton-Sales vol.)*: New York, American Institute of Mining, Metallurgy, and Petroleum Engineers, Inc., p. 326-358.
- Sumner, J.S., 1976, Principles of induced polarization for geophysical exploration: *Developments in Economic Geology 5*, New York, Elsevier Scientific Publishing Co., 165 p.
- Sverjensky, D.A., 1986, Genesis of Mississippi Valley-type lead-zinc deposits: *Annual Review of Earth and Planetary Sciences*, v. 14, p. 177-199.
- Sweeney, P.H., Harrison, E.D. and Bradley, M., 1977, Geology of the Magmont Mine, Viburnum Trend, Southeast Missouri: *Economic Geology*, v. 72, p. 365-371.
- United States Department of Agriculture, 1992, *Soil Survey of Wythe County, Virginia*: Soil Conservation Service in cooperation with Virginia Polytechnic Institute and State University, 201 p.
- Viets, J.G., Leach, D.L., Lichte, F.E., Hopkins, R.T., Gent, C.A., and Powell, J.W., in press, Paragenetic and minor and trace-element studies of Mississippi Valley-type ore deposits of the Cracow-Silesia district, southern Poland: *Prace Geologiczne (Polish Geological Institute Quarterly)*.
- Virginia Water Control Board, 1990a, *Virginia water quality assessment, 1990*: Richmond, Virginia Water Control Board Information Bulletin 579, v. 1, variously paginated.
- _____ 1990b, *Virginia water quality assessment, 1990*: Richmond, Virginia Water Control Board Information Bulletin 579, v. 2, variously paginated.

**SOLUTION-COLLAPSE BRECCIA PIPE U DEPOSITS
MODEL 32e; Finch, 1992)**

by Karen J. Wenrich, Bradley S. Van Gosen, and Warren I. Finch

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

These deposits consist of pipe-shaped breccia bodies formed by solution collapse and contain uraninite, and associated sulfide and oxide minerals of Cu, Fe, V, Zn, Pb, Ag, As, Mo, Ni, Co, and Se with high acid-generating capacity. Ore minerals are restricted to the near-vertical breccia pipe and surrounding ring fracture zone. Host rocks include limestone and calcareous sandstone, both with high acid-buffering capacity.

Examples

Orphan Lode (Chenoweth, 1986; Gornitz and others, 1988); Hack 1, 2, and 3 (Chenoweth, 1988; Rasmussen and others, 1986); Pigeon (Schafer, 1988); Kanab North (Mathisen, 1987); Canyon (Casadevall, 1989); Ridenour (Wenrich and others, 1990; Verbeek and others, 1988; Chenoweth, 1988); these deposits are located in the northern Arizona breccia pipe district (fig. 1), which is the largest breccia-pipe-hosted uranium province in the world. Similar deposits located elsewhere include Apex, southwest Utah (Wenrich and others, 1987; Verbeek and others, 1987); Temple Mountain, Utah (Hawley and others, 1965); Pryor Mountains, south-central Mont. (Hauptman, 1956; McEldowney and others, 1977; Patterson and others, 1988); Tsumeb, Namibia (Lombaard and others, 1986).

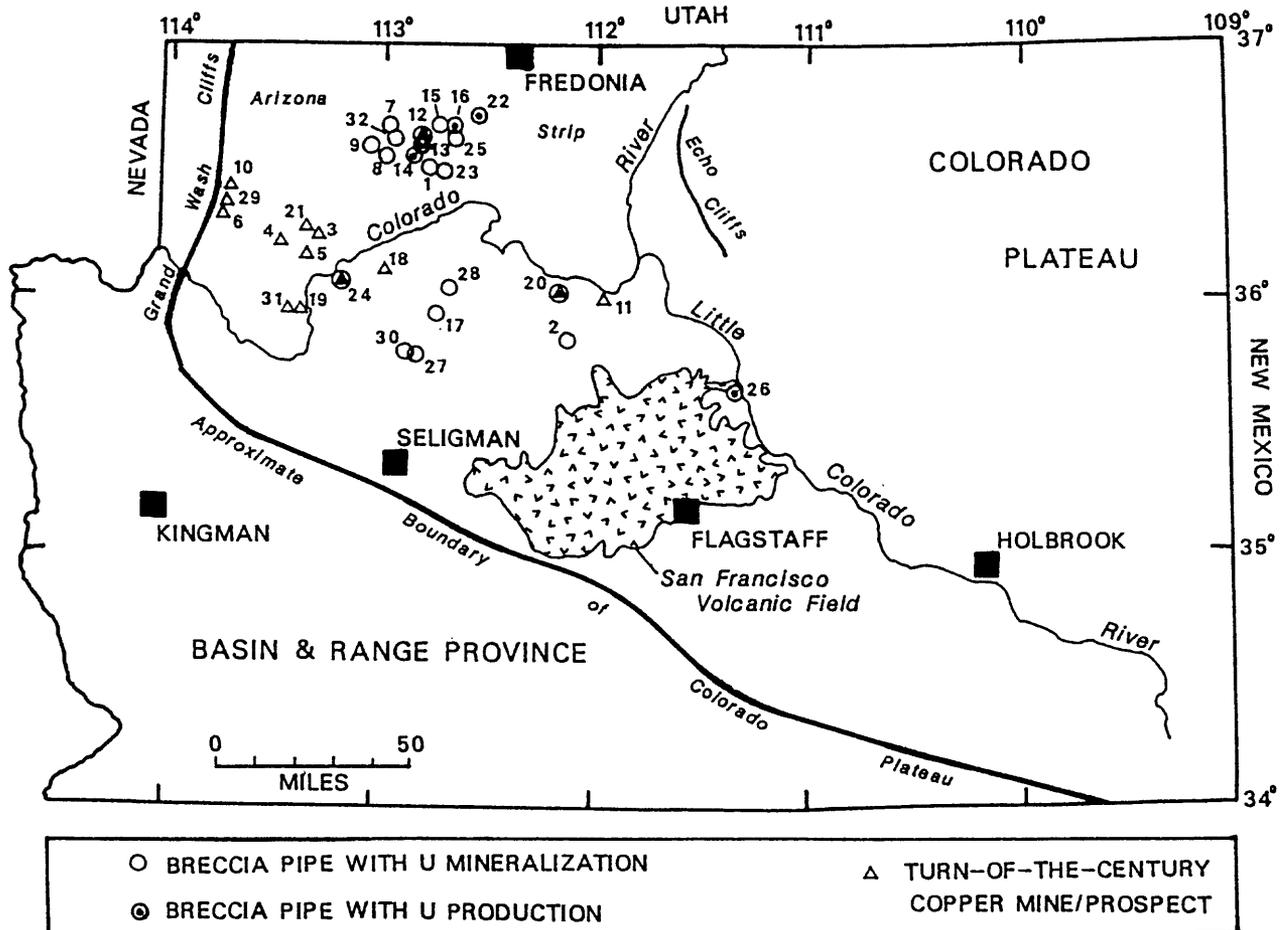


Figure 1. Index map of northern Arizona showing locations of mineralized breccia pipes, and San Francisco volcanic field that buries terrane with high potential for breccia pipes (Wenrich and others, 1989). Numbers refer to the following mines: (1) Arizona 1, (2) Canyon, (3) Chapel, (4) Copper House, (5) Copper Mountain, (6) Cunningham, (7) DB-1, (8) EZ-1, (9) EZ-2, (10) Grand Gulch, (11) Grandview, (12) Hack 1, (13) Hack 2, (14) Hack 3, (15) Hermit, (16) Kanab North, (17) Lynx, (18) Mohawk Canyon, (19) Old Bonnie Tunnel, (20) Orphan, (21) Parashant, (22) Pigeon, (23) Pinenut, (24) Ridenour, (25) Rim, (26) Riverview, (27) Rose, (28) Sage, (29) Savannic, (30) SBF, (31) Snyder, (32) What.

Spatially and (or) genetically related deposit types

None of the Cox and Singer (1986) models are known to be genetically related to solution-collapse breccia pipe deposits. Breccia pipe deposits are, however, spatially associated with uranium concentrations in paleostream channel deposits and Shinarump ore, hosted by the Chinle Formation near Cameron, Ariz. Cameron area ore may be genetically related; it may have been deposited from breccia pipe mineralizing fluids that moved up and laterally outward (Wenrich and others, 1989). Breccia pipe deposits are also spatially associated with Kaibab Limestone stratiform copper deposits (Van Gosen and Wenrich, in press).

Potential environmental considerations

Potential geoenvironmental considerations associated with breccia pipe deposits include:

- (1) Radon and gamma radiation associated with active and abandoned mines, dumps, and tailings; radon in caves.
- (2) Contamination related to transporting radioactive ore along highways in route to processing facilities.
- (3) Radioactive elements and toxic metals in mill tailings.
- (4) Acid drainage and toxic metals (such as arsenic, lead, and zinc) could be a problem in the immediate vicinity of mineralized pipes where they are dissected and exposed to flooding and catastrophic precipitation. In general, limestone and calcareous sandstone host rocks efficiently buffer acidic runoff water, and buffer downward percolating water prior to, or during, their transport in aquifer systems.

Exploration geophysics

Electrical conductivity and magnetic properties of the pipes are distinct relative to those of unbrecciated host rocks. Diagnostic differences in conductivity have been identified by scalar audiomagnetotelluric and E-field telluric profile data for at least one ore-bearing pipe (Flanigan and others, 1986). Ground magnetometer surveys show subtle magnetic lows over several pipes, perhaps indicating alteration of detrital magnetic minerals within reduced zones associated with uranium deposits (Van Gosen and Wenrich, 1989). Breccia pipe locations are spatially unrelated to magnetic lineations defined by a high resolution aeromagnetic survey (Flanigan and others, 1986). High-grade uranium ore in northern Arizona breccia pipes is generally deeply buried (>300 m); associated gamma-radiation is essentially undetectable at the surface (Wenrich, 1986). Detailed gamma-radiation surveys of more than 1000 breccia pipe and collapse features indicate that few pipes have associated gamma radiation that is more than five times background levels (Wenrich, 1985). Scarce gamma radiation anomalies detected at the surface are coincident with ring fracture zones and are of limited areal extent (<1 m in diameter) (Wenrich, 1985). The limited size of these anomalies is responsible for the fact that an airborne radiometric survey, flown about 120 m above ground, over this area at 5 (east-west) and 10 (north-south) km flight-line spacings (LKB Resources, Inc., 1979) identified no anomalies associated with known deposits (fig. 1). In limestone karst-hosted uranium-vanadium deposits of the Pryor Mountains, Mont., minor increases in radioactivity (twice background level) were measured directly over mineralized fractures, but no anomalous radioactivity was identified near karst pits (Patterson and others, 1988).

References

Hauptman (1956), Wenrich and others (1989), Wenrich and Sutphin (1989), and Finch (1992), Finch and others (1992).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Most deposits are of small to intermediate size. Production and reserves associated with northern Arizona pipes include 0.1 to 0.5 million metric tonnes of ore (Finch and others, 1992). Production and reserves from the Tsumeb deposit include 22 million metric tonnes of ore (Lombaard and others, 1986). Deposits in the Pryor Mountains are very small (Hauptman, 1956).

Host rocks

Host rocks include breccias of limestone, sandstone, siltstone, and shale in a finely comminuted sand matrix cemented by carbonate minerals.

Surrounding geologic terrane

These deposits are in alternating sequences of sandstone, siltstone, shale, and limestone strata overlying paleokarst with open and paleo-sandstone-filled channels and caverns.

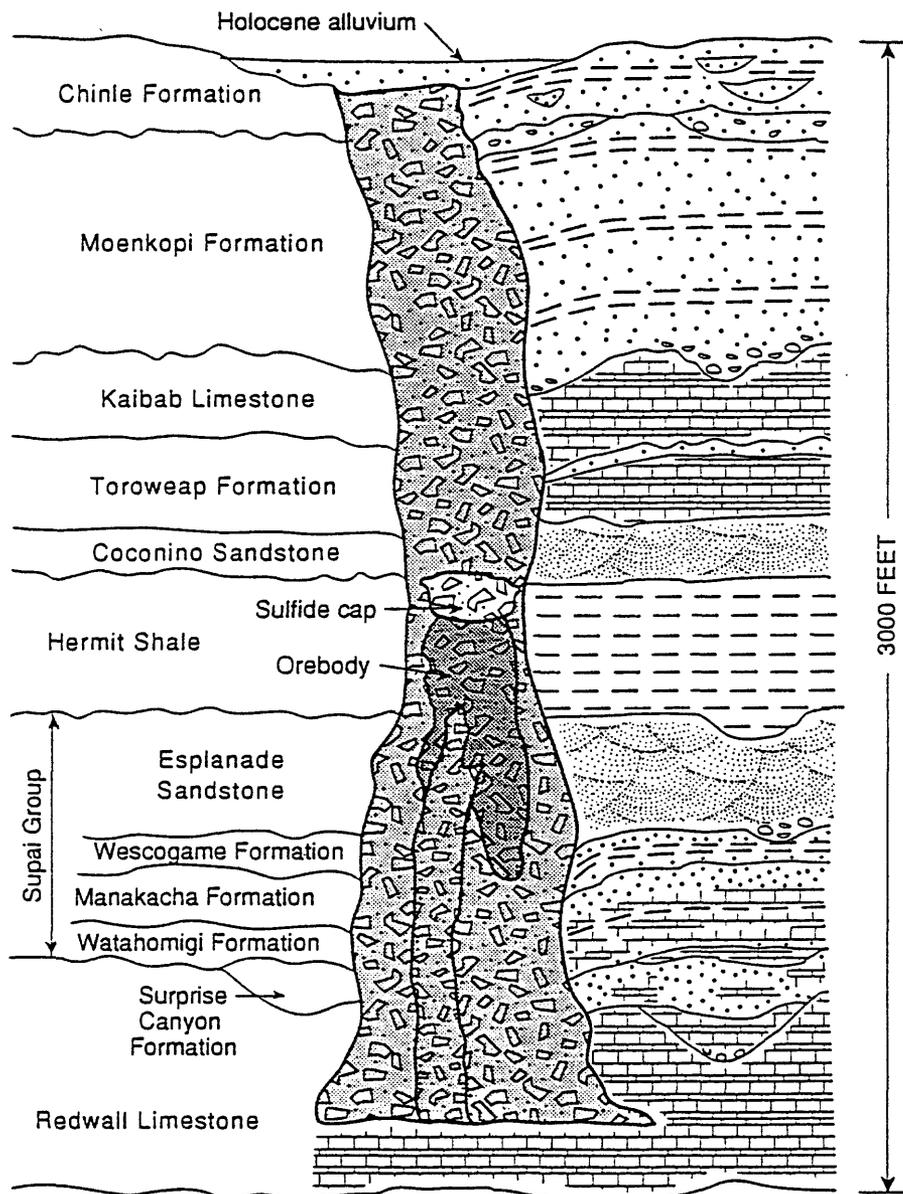


Figure 2. Simplified geologic cross section of northern Arizona breccia pipe showing dimensions and stratigraphic setting of breccia pipe, uranium-sulfide ore, and sulfide mineral "cap" (Wenrich and Aumente-Modreski, in press). Typical diameter of pipe is 100 m.

Wall-rock alteration

The principal form of wall-rock alteration associated with these deposits is bleaching (oxidation) of iron oxide minerals in red sandstone by reducing fluids. Alteration extends 30 to 100 m outward into wall rock of Grand Canyon, Ariz., region deposits and less than 10 m into wall rock of Pryor Mountains, Mont., deposits.

Nature of ore

Nearly all primary ore is confined to breccia pipes (fig. 2); the only major exception is the local presence of ore in ring fracture zones in country rocks surrounding pipes. The vertical position of most primary ore in the Grand Canyon breccia pipe is at the Coconino Sandstone, Hermit Shale, and Esplanade Sandstone (all Permian) stratigraphic horizons.

Deposit trace element geochemistry

Randomly collected breccia pipe rock samples contain elevated abundances of a number of elements, including <2

to 2,400 ppm Ag, 0.5 to 111,000 ppm As, 4 to 100,000 ppm Ba, <2 to 2,900 ppm Cd, 0.66 to 26,000 ppm Co, <1 to 290,000 ppm Cu, <0.01 to 140 ppm Hg, <2 to 24,000 ppm Mo, <2 to 62,000 ppm Ni, <4 to 84,000 ppm Pb, 0.13 to 2,900 ppm Sb, <0.10 to 3,000 ppm Se, 4 to 5,800 ppm Sr, 0.63 to >210,000 ppm U, <4 to 50,000 ppm V, and <4 to 260,000 ppm Zn (K.J. Wenrich, unpub. data, 1995).

Ore and gangue mineralogy and zonation (see Wenrich and Sutphin, 1988, 1989)

Potentially acid-generating minerals underlined. Primary ore minerals include uraninite, sphalerite, galena, nickeline, rammelsbergite, pararammelsbergite, gersdorffite, bravoite, siegenite, vaesite, millerite, skutterudite, Co-gersdorffite, linnaeite, stibnite, molybdenite, enargite, chalcopyrite, lautite, tennantite, tetrahedrite, pyrite, marcasite, arsenopyrite. Primary gangue minerals include barite, quartz, chalcedony, pyrobitumen, kaolinite, calcite, dolomite, ankerite, siderite, anhydrite and fluorite.

Zoning: The only recognized zoning in primary orebodies involves concentration of nickel-cobalt-iron-copper arsenide and sulfide minerals in sulfide caps above ore. Secondary and supergene minerals are present where ore has been exposed to oxidation, including canyon dissection and fracture-controlled oxidation (Verbeek and others, 1988; Wenrich and others, 1990).

Mineral characteristics

Textures: Uraninite, other oxide minerals, and sulfide minerals are very fine grained (generally <1 mm); rarely, primary mineral grains are as large as 1 cm. Secondary mineral grains, commonly as much as 1 cm, tend to be larger than those of primary minerals.

Trace element contents: Primary and secondary minerals can include any of the following: Ag, As, Ba, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Sb, Se, Sr, U, V, Y, and Zn.

General rates of weathering: These deposits weather rapidly. Primary ore can oxidize within six months when exposed to surface weathering. Within six months of opening drifts in underground breccia pipe mines in the Grand Canyon area, some uraninite has altered to hexavalent secondary minerals, primary cobalt-bearing sulfide minerals to erythrite, and molybdenite to ilsemanite.

Secondary ore and gangue mineralogy

Secondary ore and gangue minerals include tyuyamunite, metatyuyamunite, zippeite, zeunerite, metazeunerite, metatorbernite, uranophane, bayleyite, uranospinite, adamite, smithsonite, aurichalcite, hemimorphite, anglesite, cerussite, wulfenite, rhodochrosite, hewettite, vesignieite, volborthite, calciovolborthite, roscoelite, erythrite, bieberite, ilsemanite, chalcocite, djurleite, digenite, covellite, bornite, cuprite, tenorite, chrysocolla, azurite, malachite, olivenite, chalcantite, brochantite, cyanotrichite, chalcoalumite, langite, antlerite, devilline, conichalcite, acanthite, naumannite, proustite, scorodite, melanterite, limonite, hematite, goethite, siderotil, coquimbite, jarosite, celadonite, illite, gypsum, hexahydrite, and leonhardtite (Wenrich and Sutphin, 1988).

Topography, physiography

Solution-collapse breccia pipes are distinguished by concentric-inward-dipping beds that generally surround a basin, amphitheater-style erosion, concentric drainage, soil and vegetation patterns, breccia, and altered and mineralized rock (Wenrich and Sutphin, 1988). Locally, breccia plugs are silicified and more resistant to erosion. These plugs form erosional spires or pinnacles in which ore has been oxidized; most trace metals have been leached from these pipes. Ring fractures surrounding the pipes tend to erode readily, which causes development of concentric drainage around pipes.

Hydrology

Ring fracture zones: These zones have high permeability and therefore locally focus ground water flow. Breccia in solution collapse pipes is also relatively permeable where not silicified. However, in the Grand Canyon area, ground water within 600 m of the plateau surface is rare. Consequently, unless canyon dissection has altered this situation or a perched aquifer is present, very little water moves downward into the pipes because orebodies are located, on average, 300 m below the surface.

Aquifers: Major aquifers in the Grand Canyon region are the Mississippian Redwall Limestone and the Cambrian Muav Formation; both lie several hundred feet below the breccia pipe orebodies. However, in the Pryor Mountains, south-central Mont., uranium minerals are oxidized and are within paleokarst and modern karst of the Mississippian Madison Limestone (stratigraphic equivalent of the Redwall Limestone); this karst is a major aquifer in the region,

and therefore plays a major role in uranium oxidation and mobility.

Mining and milling methods

Historic: Typical underground workings followed ring fracture zones in oxidized breccia pipes. Historic mines (fig. 1) produced copper, lead, zinc and silver ore (Billingsley, 1974; Chenoweth, 1988; Wenrich and Sutphin, 1988). Modern: Uranium was not recognized in the breccia pipes until 1951 (Chenoweth, 1986). All modern mines have been underground operations. During the 1960s, ore from breccia pipes in the Grand Canyon region was shipped to a mill in Tuba City (where copper and vanadium were also extracted); since the 1980s it has been shipped to a mill in Blanding, Utah. Uranium ore is dissolved by either acid or alkaline solutions, and uranium is precipitated by either ion-exchange or solvent extraction; in either case, the product, commonly ammonium diuranate, is called "yellowcake" because of its color (Cooper, 1986).

ENVIRONMENTAL SIGNATURES

Drainage signatures

Mine-drainage data: No data available for the Grand Canyon, Ariz., area; no surface water drains the immediate vicinity of mines. Warchola and Stockton (1982) found no significant uranium enrichment in water draining uranium deposits in the Pryor Mountains, Mont. More water sampling adjacent to mine areas is needed in both Arizona and Montana.

Natural-drainage data: Data are available for north Grand Canyon rim springs (Billingsley and others, 1986) and south Grand Canyon rim springs and surface water, including Hualapai Indian Reservation (Wenrich and others, 1994). Grand Canyon area water is primarily of the calcium-magnesium-bicarbonate type, although some is of the sulfate and chloride types, which tend to have higher natural trace metal contents. The few spring water samples collected near mines tend to have metal contents that are similar to, though somewhat more elevated than, those of some sulfate-type water (Billingsley and others, 1986; Wenrich and others, 1994).

Metal mobility from solid mine wastes

Solid waste resulting from mining breccia pipe deposits is very limited. No data pertaining to quantities of metals mobilized by limited quantities of water interacting with these wastes are available.

Soil, sediment signatures prior to mining

Extensive soil sampling surveys in the Grand Canyon region provide elemental abundance levels in (1) regional soil, (2) soil over mineralized breccia pipes, and (3) soil over unmineralized breccia pipes (Van Gosen and Wenrich, 1991; Wenrich and Aumente-Modreski, 1994). In addition, stream sediment samples were collected during the National Uranium Reconnaissance Evaluation (Wagoner, 1979; Koller, 1980). A few additional stream-sediment samples were collected by Billingsley and others (1986). The exceptionally small size (diameters generally less than 100 m) of these deposits, and exceptionally weak associated geochemical halos (commonly less than 2.5 times background) preclude detection of most mineralized breccia pipes using stream-sediment samples (Wenrich, 1986). Similarly, Patterson and others (1988) conducted a stream-sediment sampling program in the Pryor Mountains, Mont., an area known to contain uranium occurrences. Samples collected immediately downstream from known deposits contained less than 4 ppm uranium. Their sampling failed to identify previously unknown uranium occurrences. Consequently, these deposits have essentially no pre-mining geochemical signature.

Potential environmental concerns associated with mineral processing

Mineral processing is not done on site. Ore is sorted from waste on site and shipped to mills for processing. On site environmental concerns include radon from mines and gamma radiation from ore and waste piles. Reclamation entails backfilling mines with waste rock and sealing mine entrances to prevent radon leakage and future entry.

Mill signatures

Tailings at mineral processing sites are a major environmental concern because of their large volume and fine-grain size, which permits redistribution by wind. Large tailing piles emit abundant radon and gamma radiation; if water circulates through tailings and escapes from ponds, local aquifers and drainages may be contaminated. Potential water contamination may be a particularly serious problem during periods of severe weather or from stress failure of dams. For example, "on July 16, 1979, the failure of an earthen dam, which held back uranium-mining and milling wastewater and sediment, released about 94 million gallons of highly acidic liquid and 1,100 tons of uranium-

mine tailings to the Puerco River through Pipeline Arroyo....Three months to a few years following the spill, several scientific studies concluded that no trace of sediment containing radium and thorium from the spill could be identified, although the Puerco River was still receiving high amounts of dissolved uranium from mine dewatering" (Wirt, 1994). Although these were not breccia pipe mine tailings, they exemplify the potential problem of uranium tailings. However, although this was the largest single release of uranium mine tailings in United States history, the long term and long distance effects of uranium contamination on the environment in the Rio Puerco, N. Mex. and Ariz., drainage appear to be negligible (Wirt, 1994).

Environmental mitigation

Environmental mitigation should include complete surface reclamation, as done in the area of the Hack and Pigeon, Ariz., mines (see photographs in Finch, 1994). Mines should be sealed, dumps and tailings should be backfilled into mines, and mine areas revegetated.

Climate effects on environmental signatures

In the Grand Canyon region the climate is arid, which greatly retards orebody oxidation and the movement of trace metals in the environment. The effects of other climate regimes on the geoenvironmental signature specific to these deposits has not been documented. However, in most cases the intensity of environmental impact associated with sulfide-mineral-bearing deposits is greater in wet climates than in dry climates. Acidity and total metal concentrations in mine drainage in arid environments are several orders of magnitude greater than in more temperate climates because of the concentrating effects of mine effluent evaporation and the resulting "storage" of metals and acidity in highly soluble metal-sulfate-salt minerals. However, minimal surface water flow in these areas inhibits generation of significant volumes of highly acidic, metal-enriched drainage. Concentrated release of these stored contaminants to local watersheds may be initiated by precipitation following a dry spell.

Geoenvironmental geophysics

Electromagnetic and direct current resistivity or induced polarization surveys can be used to map acidic drainage and water with increased metal content escaping from mill tailings. Detailed ground or airborne gamma radiation surveys can be used to detect or monitor radioactive contamination related to flooding and ore transportation and processing.

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REFERENCES CITED

- Billingsley, G.H., 1974, Mining in Grand Canyon, *in* Breed, W.J., and Roat, E.C., eds., *Geology of the Grand Canyon: Museum of Northern Arizona and Grand Canyon Natural History Association*, p. 170-185.
- Billingsley, G.H., Antweiler, J.C., Lucchitta, Ivo, Beard, L.S., and Lane, M.E., 1986, Mineral resource potential of the Pigeon Canyon, Nevershine, and Snap Point Wilderness study areas, Mohave County, Arizona: U.S. Geological Survey Miscellaneous Investigations Series Map MF-1860-A, 10 p. pamphlet, scale 1:50,000.
- Casadevall, W.P., 1989, Exploration geology of Canyon breccia pipe south of Grand Canyon, Arizona [abs.]: *American Association of Petroleum Geologists Bulletin*, v. 73/9, p. 1150.
- Chenoweth, W.L., 1986, The Orphan Lode mine, Grand Canyon, Arizona, a case history of a mineralized, collapse-breccia pipe: U.S. Geological Survey Open-File Report 86-510, 126 p.
- _____ 1988, The production history and geology of the Hacks, Ridenour, Riverview and Chapel breccia pipes, northwestern Arizona: U.S. Geological Survey Open-File Report 88-0648, 60 p.
- Cooper, W.C., 1986, Uranium production, *in* Bever, M.B., ed., *Encyclopedia of Materials Science Engineering*: Oxford, England, Pergamon Press, v. 7, p. 5215-5218.
- Cox, D.P. and Singer, D.A., 1986, Mineral Deposit Models: U.S. Geological Survey Bulletin 1693, 379 p.
- Finch, W.I., 1992, Descriptive model of solution-collapse breccia pipe uranium deposits, *in* Bliss, J.D., ed., *Developments in mineral deposit modeling*: U.S. Geological Survey Bulletin 2004, p. 33-35.
- _____ 1994, The environment and the geology of uranium: Selected Issues in the USGS Energy Resource Surveys Program, April 1994, 2 p.
- Finch, W.I., Pierson, C.T., and Sutphin, H.B., 1992, Grade and tonnage model of solution collapse breccia pipe uranium deposits, *in* J.D. Bliss, ed., *Developments in mineral deposit modeling*: U.S. Geological Survey Bulletin 2004, p. 36-38.

- Flanigan, V.J., Mohr, P.J., Tippens, Charles, and Senterfit, R.M., 1986, Electrical character of collapse breccia pipes on the Coconino Plateau, northern Arizona: U.S. Geological Survey Open-File Report 86-521, 50 p.
- Flanigan, V.J., Webring, M.W., and Mohr, P.J., 1986, Preliminary geologic interpretation of the high resolution aeromagnetic map of part of the Coconino Plateau, Hualapai Indian Reservation, Arizona: U.S. Geological Survey Open-File Report 87-53, 8 p.
- Gornitz, Vivien, Wenrich, K.J., Sutphin, H.B., and Vidale-Buden, R., 1988, Origin of the Orphan mine breccia pipe uranium deposit, Grand Canyon, Arizona, *in* Vassiliou, A.H., Hausen, D.M., and Carson, D.J., eds., *Process mineralogy VII--As applied to separation technology*: Warrendale, Penn., The Metallurgical Society, p. 281-301.
- Hauptman, C.M., 1956, Uranium in the Pryor Mountain area of southern Montana and northern Wyoming: *Uranium and Modern Mining*, v. 3, no. 11, p. 14-21.
- Hawley, C.C. Wyant, D.G., and Brooks, D.B., 1965, Geology and uranium deposits of the Temple Mountain District, Emery County, Utah: U.S. Geological Survey Bulletin 1192, 154 p.
- Koller, G.R., 1980, Hydrogeochemical and stream-sediment reconnaissance data report, Grand Canyon NTMS area, Arizona, E.I. du Pont de Nemours and Co. Aiken, South Carolina, 49 p.
- LKB Resources, Inc., 1979, NURE aerial gamma-ray and magnetic reconnaissance survey, Colorado-Arizona area, Grand Canyon NJ 12-10 quadrangle: U.S. Department of Energy Open-file Report GJBX-35-80, 120 p., 2 microfisch plates.
- Lombaard, A.F., Günzel, A., Innes, J., and Krüger, T.L., 1986, The Tsumeb lead-copper-zinc-silver deposit, South West Africa/Namibia, *in* Anhaeusser, C.R., and Maske, S., eds., *Mineral deposits of Southern Africa*, vols. I & II: Geological Society of South Africa, Johannesburg, p. 1761-1787.
- Mathisen, I.W., Jr., 1987, Arizona Strip breccia pipe program--Exploration, development, and production [abs.]: *American Association of Petroleum Geologists Bulletin*, v. 71/5, p. 590.
- McEldowney, R.C., Abshier, J.F., and Lootens, D.J., 1977, Geology of uranium deposits in the Madison Limestone, Little Mountain area, Big Horn County, Wyoming, *in* Veal, H.K., ed., *Exploration frontiers of the Central and Southern Rockies*: Rocky Mountain Association of Geologists, p. 321-336.
- Patterson, C.G., Toth, M.I., Kulik, D.M., Esparza, L.E., Schmauch, S.W., and Benham, J.R., 1988, Mineral resources of the Pryor Mountain, Burnt Timber Canyon, and Big Horn tack-on wilderness study areas, Carbon County, Montana, and Big Horn County, Wyoming: U.S. Geological Survey Bulletin 1723, 15 p.
- Rasmussen, J.D., Cunningham, C.G., and Gautier, A.M., 1986, Primary fluid inclusions in sphalerite from the Hack 1 and 2 mines, Mohave County, Arizona: *Geological Society of America Abstracts with Programs*, v. 18, no. 5, p. 404.
- Schafer, R.N., 1988, An example of a northern Arizona solution-collapse breccia pipe--Geology of the Pigeon mine [abs.]: *Geological Society of America Abstracts with Programs*, v. 20, no. 7, p. A139.
- Van Gosen, B.S., and Wenrich, K.J., 1989, Ground magnetometer surveys over known and suspected breccia pipes on the Coconino Plateau, northwestern Arizona: U.S. Geological Survey Bulletin 1683-C, 31 p.
- _____ 1991, Geochemistry of soil samples from 50 solution-collapse features on the Coconino Plateau, northern Arizona: U.S. Geological Survey Open File Report 91-0594-A Discussion (paper copy), 281 p.; 91-0594-B Geochemical data files (diskette); 91-0594-C Geochemical data files (diskette); 91-0594-D Geochemical data files (diskette).
- _____ in press, Strata-bound copper deposits in the Kaibab Limestone, Coconino County, northern Arizona: U.S. Geological Survey Bulletin on Kaibab National Forest, 38 p.
- Verbeek, E.R., Grout, M.A., and Van Gosen, B.S., 1988, Structural evolution of a Grand Canyon breccia pipe--The Ridenour copper-vanadium-uranium mine, Hualapai Indian Reservation, Coconino County, Arizona: U.S. Geological Survey Open-File Report 88-006, 75 p.
- Verbeek, E.R., Grout, M.A., Van Gosen, B.S., and Sutphin, H.B., 1987, Structure of the Apex mine, southwestern Utah [abs.]: *Geological Society of America Abstracts with Programs*, v. 19, no. 5, p. 340.
- Wagoner, J.L., 1979, Hydrogeochemical and stream-sediment reconnaissance basic data report for Williams NTMS Quadrangle, Arizona: Lawrence Livermore Laboratory, Livermore, Ca., 72 p.
- Warchola, R.J., and Stockton, T.J., 1982, National Uranium Resource Evaluation, Billings quadrangle, Montana: U.S. Department of Energy publication No. PGJ/F-015(82), prepared for the U.S. Department of Energy, Grand Junction, Colo., by Bendix Field Engineering Corp., Grand Junction Operations, 33 p., 25 plates.
- Wenrich, K.J., 1985, Mineralization of breccia pipes in northern Arizona: *Economic Geology*, v. 80, p. 1722-1735.

- _____ 1986, Geochemical exploration for mineralized breccia pipes in northern Arizona, U.S.A.: Applied Geochemistry, v. 1, no. 4, p. 469-485.
- Wenrich, K.J., and Aumente-Modreski, R.M., 1994, Geochemical soil sampling for deeply-buried mineralized breccia pipes, northwestern Arizona: Applied Geochemistry, v. 9, p. 431-454.
- _____ in press, Geochemical soil surveys over solution-collapse features and mineralized breccia pipes, northwestern Arizona--Exploration and environmental applications: U.S. Geological Survey Bulletin 1683-E.
- Wenrich, K.J., Boundy, S.Q., Aumente-Modreski, R.M., Schwarz, S.P., Sutphin, H.B., and Been, J.M., 1994, A hydrogeochemical survey for mineralized breccia pipes--Data from springs, wells, and streams on the Hualapai Indian Reservation, northwestern Arizona: U.S. Geological Survey Open-File Report 93-619, 66 p.
- Wenrich, K.J., Chenoweth, W.L., Finch, W.I., and Scarborough, R.B., 1989, Uranium in Arizona, in Jenney, J.P., and Reynolds, S.J., eds., Geologic evolution of Arizona: Arizona Geological Society Digest 17, p. 759-794.
- Wenrich, K.J., and Sutphin, H.B., 1988, Recognition of breccia pipes in northern Arizona, in Fieldnotes: Tucson, Arizona, Arizona Bureau of Geology and Mineral Technology, v. 18, no. 1, p. 1-5, 11.
- _____ 1989, Lithotectonic setting necessary for formation of a uranium rich, solution collapse breccia pipe province, Grand Canyon region, Arizona, in Metallogenesis of uranium deposits, Proceedings of a technical committee meeting on metallogenesis of uranium deposits organized by the International Atomic Energy Agency and held in Vienna, 9-12 March 1987: Vienna, Austria, International Atomic Energy Agency, p. 307-344.
- Wenrich, K.J., Verbeek, E.R., Sutphin, H.B., Modreski, P.J., Van Gosen, B.S., and Detra, D.E., 1990, Geology, geochemistry, and mineralogy of the Ridenour mine breccia pipe, Arizona: U.S. Geological Survey Open-File Report 90-0504, 66 p.
- Wenrich, K.J., Verbeek, E.R., Sutphin, H.B., Van Gosen, B.S., and Modreski, P.J., 1987, The Apex mine, Utah--A Colorado Plateau-type solution-collapse breccia pipe [abs.], in Sachs, J.S., ed., USGS research on mineral resources--1987 program and abstracts: U.S. Geological Survey Circular 995, p. 73-74, 76-77.
- Wirt, Laurie, 1994, Radioactivity in the environment--A case study of the Puerco and Little Colorado River basins, Arizona and New Mexico: U.S. Geological Survey Water-Resources Investigations Report 94-4192, 23 p.

SUPERIOR FE DEPOSITS (MODEL 34a; Cannon, 1986)

by William F. Cannon, Donald G. Hadley, and Robert J. Horton

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Superior-type iron-formation consists of extensive stratigraphic units of iron-rich rocks interbedded with a variety of shallow water marine sedimentary rocks, including quartzite, shale, and dolomite, that are part of sedimentary sequences that lie unconformably on older crystalline basement rocks, either in passive margin or foreland basin settings. Some Superior-type iron-formation interfingers with or grades laterally into volcanic rocks; most is Early Proterozoic or very late Archean in age. Oxide, carbonate, and silicate facies are commonly interbedded, and sulfide facies is present in some cases. Economic deposits are restricted to oxide facies ore, commonly referred to as taconite in North America (in some areas "taconite" has a specific legal definition for taxation purposes), from which concentrates of magnetite and less commonly hematite can be produced. All ore requires concentration, done at or near the mine site, to produce a marketable product. Individual mines generally exploit only a small part of the iron-formation. Mine boundaries may be determined by subtle features of mineralogy, structure, or other geologic and geotechnical factors, or by property or political boundaries. In some cases, as on the Mesabi Iron Range, Minn., a series of mines forms nearly continuous workings for many kilometers along strike of the iron-formation. Deposits of this type provide nearly all domestic iron production; the Mesabi Range, Minn., and Marquette Range, Mich., are the major producing districts. Their combined production is about 50 million tonnes per year.

Examples

Mesabi Iron Range, Minn. (Biwabik Iron-Formation); Marquette Iron Range, Mich. (Negaunee Iron-Formation); Minas Gerais area, Brazil; Wabush Lake area, Canada

Spatially and (or) genetically related deposit types

Some Superior-type iron-formation, such as the Kalahari district of South Africa, includes interbedded manganese-rich strata that may constitute important manganese ore.

Potential environmental considerations

Geoenvironmental concerns are almost entirely related to physical redistribution of earth materials; concerns related to acid water generation and metal mobility are minor. Many taconite mines in Superior-type iron-formation rank among the world's largest mines. Exceptionally large open pits, waste rock dumps, and tailings impoundments produce long-term modifications of the Earth's surface.

Processing taconite to concentrate iron minerals produces large volumes of fine-grained tailings that must be permanently stored. The tailings consist of quartz, a variety of silicate minerals, some of which may be fibrous, iron carbonate minerals, and iron oxide minerals. Potential environmental concerns related to tailings include: (1) silica-rich wind-borne dust, (2) fibrous silicate minerals in air and water, (3) particulate and colloidal iron compounds in discharge water, (4) exchange of water in tailings impoundments with ground water, (5) long-term stability of tailings impoundments, and (6) mineral dusts in stack emissions from kilns.

Ore that contains amphibole minerals is a particular concern because it has the potential to generate fine-grained acicular cleavage fragments that meet some legal definitions of asbestos; natural amphibole asbestos poses similar problems. Crocidolite, the fibrous variety of riebeckite, and amosite, the fibrous variety of grunerite-cummingtonite amphibole, are known carcinogens of both the lungs and digestive tract and can be harmful, even with less than occupational exposure. Both minerals are present in some iron-formation but are far from ubiquitous. The non-asbestiform variety of grunerite-cummingtonite amphibole is common in iron-formation, including much that is mined and processed. Fine acicular particles, legally classed as asbestos, that are produced by grinding are potentially harmful. However, epidemiological studies of taconite miners and mill workers at a taconite mine in Minnesota, where the ore contains abundant grunerite-cummingtonite, found no evidence of excess cancer of the type related to asbestos exposure (Ross, 1984). Nevertheless, any iron-formation containing amphibole probably requires special consideration with regard to mine design, milling, and waste disposal practices to minimize discharge of amphibole particles into the environment. All of these hazards are successfully mitigated at numerous large mining and processing operations.

Superior-type deposits are invariably mined from open pits resulting in large, and partly permanent surface disturbance. Reclamation after mining generally only partly restores pre-mining surface configuration.

Exploration geophysics

Gravity and magnetic methods can be used to delineate greenstone belts within granite-greenstone terranes at provincial to regional scales. Magnetic low and gravity high anomalies are usually associated with relatively nonmagnetic, dense greenstone terranes, whereas magnetic high and gravity low anomalies are usually associated with magnetic, low-density granitic terranes (Innes, 1960; Bhattacharya and Morely, 1965; McGrath and Hall, 1969; Tanner, 1969; and Condie, 1981). Gravity and magnetic methods can also be used for deposit-scale iron-formation studies. Most iron-formation is associated with positive, high-amplitude gravity anomalies because it contains elevated abundances of high-density iron minerals, including magnetite and hematite. The magnetic signature of iron-formation is usually one to two orders of magnitude greater than that of its host rock (Bath, 1962; Sims, 1972). Remote sensing imaging spectroscopy can also be used in regional exploration (Hook, 1990) because iron ore minerals and their alteration products have distinct spectral signatures (Clark and others, 1993).

The magnetic character of iron-formation is dependent on magnetic mineral content, alteration, structural attitude, and remanent magnetization. Iron-formation with low magnetite content, or deposits in which magnetite has been oxidized to non-magnetic hematite, produce low-amplitude anomalies of tens to hundreds of nanoTeslas. Flat-lying deposits with normal magnetic polarization typically produce positive anomalies of about several thousand nanoTesla. Steeply dipping or folded iron-formation dominated by remanent magnetic polarization can produce anomalies with extremely high positive amplitudes of as much as tens of thousands of nanoTesla.

Electrical and electromagnetic methods are generally not applied to iron-formation exploration because the ore is resistive owing to high silica (chert) content. However, electrical techniques could be used to delineate conductive sulfide facies associated with ore deposits.

References

Geology: James (1954), Beukes (1983), Morey (1983), and Trendall (1983).
Environment: Bartlett (1980), Ross (1984), Gross (1988), Myette (1991), and Ross and others (1993).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Superior-type iron-formation forms extensive stratigraphic units, some containing tens of trillions of tons of material averaging about 30 percent iron. Individual mining blocks outlined within iron-formation, based largely on metallurgical characteristics related to grinding and concentration, commonly exceed a billion tons of reserves and seldom are less than 100 million tons. Median deposit size is 170 million tonnes (Mosier and Singer, 1986).

Host rocks

Superior-type iron-formation is interbedded with marine shale, quartzite, carbonate rocks, and in some cases mafic to felsic volcanic rocks. Some contain extensive diabase sills.

Surrounding geologic terrane

Superior-type iron-formation is present in shallow marine sequences deposited on continental margins, either during passive margin phases or in foreland basins adjacent to collisional orogens. All have basement of older, generally Archean crystalline rocks. Deformation varies from mild to intense as does metamorphic grade. In some cases submarine volcanic rocks form interbeds or lateral facies equivalents.

Wall-rock alteration

No wall rock alteration is associated with Superior iron deposits. Formation of Superior-type iron-formation results from processes involving chemical sedimentation.

Nature of ore

Most ore is banded rock in which iron-rich bands are interlayered with chert bands on a scale of less than a millimeter to a few centimeters. Several depositional facies are common, including oxide, silicate, and carbonate facies. The facies may be in stratigraphic superposition within iron-formation or form lateral equivalents; sulfide facies ore is present in some cases. Oxide facies ore consists of both magnetite- and hematite-bearing rocks, and

is the only economically important facies. Grade is relatively uniform, typically about 30 to 35 weight percent iron for all facies, but may vary from 15 to 45 weight percent. Grain size and the nature of gangue minerals vary according to degree of metamorphism. A critical factor for environmental consideration is the metamorphic development of iron-amphibole, which may be released as discrete fibrous particles during processing. Iron amphibole commonly is present in middle greenschist facies or higher metamorphic grade rocks.

Deposit trace element geochemistry

The composition of Superior-type iron-formation is remarkably simple. Except for its essential constituents, iron and silica, iron-formation characteristically has very low abundances of other elements, nearly all of which are present at concentrations below average crustal abundances. Some iron-formation has somewhat elevated concentrations of phosphorous, which are present in apatite. Because phosphorous is extremely detrimental in steel manufacture, its concentration is carefully monitored during mining and high-phosphorous material is avoided.

Ore and gangue mineralogy and zonation

Ore minerals are magnetite and hematite. Gangue is mostly quartz in the form of variably metamorphosed chert beds. Other gangue minerals include, depending on original facies of deposition and degree of metamorphism, siderite or other ferruginous carbonate minerals, greenalite, minnesotaite, stilpnomelane, iron-amphibole, iron-pyroxene, garnet, and pyrite, generally present in only trace amounts. Magnetically concentrated ore may include hematite as gangue.

Mineral characteristics

The most important mineral characteristic is the presence or absence of amphibole that might contribute natural asbestos fibers or asbestos-like grains produced during processing. Amphibole is a common metamorphic mineral in iron-formation and may be present in middle greenschist or higher metamorphic grade rocks. Original grain size is also important and varies as a function of metamorphic grade. Weakly metamorphosed iron-formation is extremely fine grained and requires very fine grinding (as fine as 0.03 mm in some cases) to liberate iron minerals from gangue. More intensely metamorphosed ore is coarser grained and requires less grinding. Maximum grain size after grinding is generally about 0.1 mm, even for the most coarse grained ore. Grain size fineness is positively correlated with increased potential for problems with dust from tailings basins, colloidal and particulate suspensions of ore and gangue minerals in released process water, and higher tailings weathering rates.

Secondary mineralogy

Because tailings are generally very-fine grained, weathering and formation of secondary minerals may proceed quickly. Iron oxide minerals alter to iron hydroxide minerals. Iron silicate minerals alter to iron hydroxide minerals and clay. Most alteration minerals are highly insoluble. Sulfide minerals, mainly pyrite, may also quickly alter and generate small amounts of acid. Much ore also contains at least trace amounts of carbonate minerals, which, when present, are probably adequate to neutralize any acid generated.

Topography, physiography

Superior-type iron-formation can be present in a variety of physiographic settings. They are characteristic deposits of Precambrian shields, so many are in areas of low to moderate relief. They may also be present in high relief areas, particularly where older shields have been incorporated in younger orogenic belts. The principal topographic and physiographic concern relates to large volumes of tailings that are characteristically produced. In areas of high relief it may be difficult to site tailings impoundments with adequate volume. In settings where rapid runoff can produce flash flood hazards, impoundments must be protected from failure.

Hydrology

Hydrologic communication between ground water, waste piles, and tailings is a predictable consequence of mining. A detailed study of a taconite tailings basin in Minnesota (Myette, 1991) and its surroundings suggests that associated environmental problems are minimal. Abundances of components dissolved in water from a tailings test well are well below maximum abundances permitted by state standards for drinking water, except those for fluoride, which are about at the maximum permitted abundance. Particulate abundances in discharge water are also low except during occasional periods of very high precipitation or snow melt.

Mining and milling methods

Superior-type iron-formation is mined in open pits, and processed to high-grade concentrates that are pelletized and fire hardened in kilns at or near mine sites. Open pit mining produces relatively large volumes of waste rock that must be disposed of near mines. Mine waste generally includes shale and quartzite with which iron-formation is interlayered, and in some cases mafic rocks that intrude the iron-formation. Ore concentration generates large volumes of tailings, mostly composed of silica and lesser iron silicate and iron carbonate minerals. Stack emissions of mineral dust might also be a concern; scrubbing or filtering might be required to eliminate dust problems.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Pre-mining drainage signatures for Superior-type iron-formation deposits are unknown. In virtually all weathering regimes, original iron minerals break down to iron hydroxide minerals and clay which are highly insoluble. With intense weathering silica is lost, but not in concentrations that produce a detectable geochemical signature. Some asbestos-like particles may be released into surface water; however, the U.S. Environmental Protection Agency has concluded that ingestion of asbestos fibers poses no significant cancer risk (U.S. Environmental Protection Agency, 1991).

Metal mobility from solid mine wastes

Except in special cases, in which sulfide-mineral-rich rocks might be included in waste rock, metal mobility is probably negligible. Iron weathers to largely insoluble compounds and iron-formation contains concentrations of other metals that are at or below average crustal abundances.

Soil, sediment signatures prior to mining

Pre-mining soil and sediment signatures for Superior-type iron-formation deposits are unknown but stream sediments probably contain high iron abundances. In areas of intense weathering, very iron-rich laterite, some of which may itself be iron-ore, may develop on iron-formation. In glaciated areas, most iron formation is virtually unweathered and has no associated characteristic soil signature.

Potential environmental concerns associated with mineral processing

Most Superior-type iron-formation ore is ground to 0.1 mm or finer, concentrated by magnetic or specific gravity techniques, and formed into pellets that are then fire hardened in kilns at or near mine sites. The large volume of tailings generated are stored in nearby impoundments. The principal environmental concern involves continued physical isolation of tailings, particularly fine-grained silica and fibrous silicate minerals. Redistribution by wind can be mitigated by wetting and vegetating abandoned tailings areas. Redistribution in surface water can be minimized at active mines by reuse of tailings water so that outflow is restricted to periods of very high precipitation or snow melt. The long term, post-mining stability of tailings impoundments must be assured in their design.

Combustion products from rotary kilns are generally vented through stacks and may carry fine ore particles that should be removed by scrubbing or filtering before combustion products are released to the atmosphere.

Smelter signatures

No smelting is required to process Superior-type iron ore.

Climate effects on environmental signatures

Principal climatic concerns relate to the continued integrity of tailings impoundments in climates with high annual or seasonal precipitation and with airborne redistribution of tailings in dry climates. Even in humid climates, milling operations generally reuse nearly all process water to minimize water outflow through tailings basins. In climates susceptible to extreme precipitation, however, measures are required to assure that flooding does not compromise the containment of tailings either during or after mining.

Geoenvironmental geophysics

Electrical methods can be used to identify conductive ground water plumes produced by high abundances of dissolved solids and colloidal suspensions. The self potential method can detect leaks in tailings impoundment dikes. Remote sensing methods can be used to quantify areas of permanent surface disturbance related to mining and ore processing. Remote sensing methods may also be used to identify areas of stressed vegetation related to sulfur and fugitive-metal

stack emissions, and contaminated surface water.

REFERENCES CITED

- Bartlett, R.W., 1980, The Reserve mining controversy--Science, technology, and environmental quality: Bloomington, Indiana University Press, 293 p.
- Bath, G.D., 1962, Magnetic anomalies and magnetization of the Biwabik iron-formation, Mesabi area, Minnesota: *Geophysics*, vol. 27, p. 627-650.
- Beukes, N.J., 1983, Paleoenvironmental setting of iron-formations in the depositional basin of the Transvaal Supergroup, South Africa, *in* Trendall, A.F., and Morris, R.C., eds., *Iron-formation--Facts and problems*: New York, Elsevier Scientific Publishing Inc., p. 131-210.
- Bhattacharya, B.K., and Morley, L.W., 1965, The delineation of deep crustal magnetic bodies from total field aeromagnetic anomalies: *Journal of Geomagnetism and Geoelectronics*, v. 17, p. 237-252.
- Cannon, W.F., 1986, Descriptive model of Superior Fe, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models*: U.S. Geological Survey Bulletin 1693, p. 228.
- Clark, R.N., Swayze, G.A., and Gallagher, A., 1993, Mapping minerals with imaging spectroscopy, *in* Scott, R.W., Jr., and others, eds., *Advances related to United States and international mineral resources--Developing frameworks and exploration techniques*: U.S. Geological Survey Bulletin 2039, p. 141-150.
- Condie, K.C., 1981, *Archean greenstone belts*: Elsevier Scientific Publishing Company, 434 p.
- Gross, G.A., 1988, Gold content and geochemistry of iron-formation in Canada: Geological Survey of Canada Paper 86-19, 54 p.
- Hook, S.J., 1990, The combined use of multispectral remotely sensed data from the short wave infrared (SWIR) and thermal infrared (TIR) for lithological mapping and mineral exploration: Fifth Australasian Remote Sensing Conference, Proceedings, Oct., 1990, v. 1, p. 371-380.
- Innes, M.J.S., 1960, Gravity and isostasy in northern Ontario and Manitoba: Dominion Observatory of Ottawa Publication, v. 21, p. 261-338.
- James, H.L., 1954, Sedimentary facies of iron-formation: *Economic Geology*, v. 49, p. 235-293.
- McGrath, P.H., and Hall, D.H., 1969, Crustal structure in northwestern Ontario: Regional aeromagnetic anomalies: *Canadian Journal of Earth Science*, v. 6, p. 191-207.
- Morey, G.B., 1983, Animikie Basin, Lake Superior region, U.S.A., *in* Trendall, A.F., and Morris, R.C., eds., *Iron-formation--Facts and Problems*: New York, Elsevier Scientific Publishing Inc., p. 13-68.
- Mosier, D.L., and Singer, 1986, Grade and tonnage model of Superior Fe and Algoma Fe deposits, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models*: U.S. Geological Survey Bulletin 1693, p. 228-230.
- Myette, C.F., 1991, Hydrology, water quality, and simulation of ground-water flow at a taconite-tailings basin near Keewatin, Minnesota: U.S. Geological Survey Water-Resources Investigations Report 88-4230, 61 p.
- Ross, M., 1984, A survey of asbestos-related disease in trades and mining occupations and in factory and mining communities as a means of predicting health risks of nonoccupational exposure to fibrous minerals: American Society for Testing and Materials Special Technical Publication 834, p. 51-104.
- Ross, M., Nolan, R.P., Langer, A.M., and Cooper, W.C., 1993, Health effects of mineral dusts other than asbestos, *in* Guthrie, G.D., and Mossman, B.T., eds., *Health effects of mineral dusts*: Mineralogical Society of America, *Reviews in Mineralogy*, v. 28, p. 361-409.
- Sims, P.K., 1972, Magnetic data and regional magnetic patterns, *in* Sims, P.K., and Morey, G.B., eds., *Geology of Minnesota*, Minnesota Geological Survey, p. 585-592.
- Tanner, J.G., 1969, A geophysical interpretation of structural boundaries in the Eastern Canadian Shield: Durham, England, University of Durham, Ph.D. Dissertation.
- Trendall, A.F., 1983, The Hamersley Basin, *in* Trendall, A.F., and Morris, R.C., eds., *Iron-formation--Facts and Problems*: New York, Elsevier Scientific Publishing Inc., p. 69-130.
- U.S. Environmental Protection Agency, 1991, Final national primary drinking water rules: 56 Federal Register 3578 (Jan. 30, 1991).

SEDIMENTARY MN DEPOSITS (MODEL 34b; Cannon and Force, 1986)

by Eric R. Force, William F. Cannon, and Douglas P. Klein

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Sedimentary manganese deposits described here are shallow-marine (non-volcanogenic) deposits formed around the rims of anoxic basins during high sea-level stands at locales starved of clastic sediment. These deposits are stratiform marine basin-margin deposits, which may be present in oxide and (or) carbonate facies, in condensed stratigraphic sequences (Cannon and Force, 1986).

Examples

Molango (Jurassic), Mexico (Cannon and Force, 1986); Nikopol (Oligocene), Ukraine (Sapozhnikov, 1970); Groote Eylandt (Cretaceous), Australia (Pracejus and others, 1986); Imini (Cretaceous), Morocco (Force and others, 1986); Kalahari (Precambrian), South Africa.

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) include sedimentary phosphorite (Model 34c) and barite deposits (Model 31b); some sedimentary manganese deposits may grade into volcanogenic manganese deposits. In Precambrian sequences, close spatial and stratigraphic relations between iron formation (Model 34a) and sedimentary manganese deposits are common.

Potential environmental considerations

Potential types of geoenvironmental concern associated with these deposits include (1) manganese-rich dust, (2) elevated abundances of manganese (from carbonate-facies deposits in modern low-pH environments or oxide-facies deposits in low Eh and pH environments) in water draining these deposits, and (3) electrochemical properties of mineralized ground associated with battery-active deposits; manganese deposits, from which components used in battery manufacture are produced, can themselves act like batteries in the ground.

Effects related to each of these types of potential impact may be manifested by unmined and mined deposits and thus may be as widespread as the deposits themselves. Potential for environmental impact of the first two types is enhanced by mining; these impacts pose possible health concerns. Barium and lead abundances in these deposits may be greater than a percent; sulfide-bearing carbonate-facies deposits may contain elevated abundances of other base metals.

Examples of potential environmental impacts described above are as follows:

- (1) All oxide deposits, including exposed parts of unmined deposits, are potential sources of manganese-rich dust, which is also produced by sintering (high-temperature oxidation) plants associated with some carbonate-facies deposits (for example, Molango).
- (2) Some water draining Molango and other carbonate-facies deposits contains elevated abundances of dissolved manganese.
- (3) Groote Eylandt and other battery-active deposits that contain the oxide minerals nsutite and (or) vernadite are associated with distinctive electrochemical potential fields.
- (4) Imini and possibly other diagenetic oxide-facies deposits are characterized by elevated barium and lead abundances.
- (5) Molango and other carbonate-facies, sulfide-mineral-bearing deposits have elevated abundances of other base metals.

Exploration geophysics

Few geophysical investigations of this deposit type are known; however, deposits with similar geologic relations provide analogies. Battery-active deposits are electrochemically active, as described above; the associated self-potential field is distinctive. Aeromagnetic surveys can be used to define broad terranes permissive for the presence of this deposit type because of an association between some sedimentary manganese deposits and iron formation; most iron formation has a distinct, positive magnetic contrast with surrounding rock (U.S. Geological Survey and Corporacion Venezolana, 1993; Sangmor and others, 1982). Manganese ore minerals, including manganite,

"psilomelane" (see section below entitled "Ore and gangue mineralogy and zonation"), and pyrolusite, are dense (3.3-7.9 g/cc). Resulting dense ore and moderate deposit size (up to 10 m thick, and covering 10 km²) indicates that detailed gravity surveys may help identify these deposits (Rowston, 1965). However, many sedimentary manganese deposits are either carbonate-facies, poorly consolidated, vuggy, and (or) extremely thin, any one of which may limit the utility of gravity surveys in exploration for this deposit type (Dorr and others, 1973). In cases where strata are minimally deformed and their seismic characteristics are well known, seismic refraction or reflection can help delineate orebodies. All manganese minerals except psilomelane are conductive (Keller, 1989); psilomelane ranges from conductive to resistive. Thus, massive manganese deposits may have low associated resistivity that can be detected by electromagnetic or direct current resistivity methods; these deposits also may be identified by induced polarization surveys. The presence of elemental carbon in surrounding rocks enhances resistivity lows (Dorr and others, 1973), but also renders direct detection more ambiguous. Electrical surveys over manganese deposits have not been documented.

References

Geology: Roy (1981), Cannon and Force (1986), and Force and Cannon (1988).
Environmental geochemistry: Matrone and others (1977).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

The 10th, 50th, and 90th percentiles of tonnage for these deposits are 280, 7.3, and 0.19 million tonnes, respectively (Mosier, 1986). Deposits are typically less than 10 m thick; large deposits can cover more than 10 km².

Host rocks

Host rocks include shallow marine sedimentary rocks, most commonly carbonate rocks, clay, and glauconitic sand, commonly with shellbeds, in high-stand sequences associated with anoxic basins. Most deposits include carbonate rocks in the host sequence. Barium-, phosphorous-, and copper-enriched rocks may be spatially or stratigraphically adjacent to manganese-enriched rock. Reduced deposits such as black shale may be similarly associated with manganese-enriched rock and may contain enrichments of a variety of base metals.

Surrounding geologic terrane

Sedimentary manganese deposits are along the margins of stable cratons or in basins contained therein. Starved sedimentary basins, in which barium and phosphorous abundances in reduced facies rocks have been enriched (see section above entitled "Host rocks"), are characteristic of these deposits.

Wall-rock alteration

Alteration associated with these deposits is minor and diagenetic rather than hydrothermal in origin.

Nature of ore

Ore consists of thin beds of manganese oxide and (or) carbonate minerals, only incidentally influenced by structural features. Vertical zonation may record depositional regression at high sea-level stand. Lateral zonation may involve oxide-facies to carbonate-facies transitions.

Deposit trace element geochemistry

The geochemistry of these deposits is variable; barium, lead, and phosphorous may be major constituents, whereas any base metal capable of adsorption on manganese oxide minerals may be present in trace amounts.

Ore and gangue mineralogy and zonation

Oxide-facies deposits: Ore- Cryptomelane-group minerals and pyrolusite are common in the most oxic deposits. Less-oxic deposits contain manganite, braunite, and kutnahorite. "Psilomelane" and "wad" (primary and supergene iron and manganese oxide mineral intergrowths) commonly are listed in older literature. Over forty oxide minerals are potential ore constituents; additional mineralogic description here is restricted to potentially environmentally problematic minerals. Among these are coronadite and hollandite, because of their elevated lead and barium contents, respectively, and nsutite and vernadite, because of their electrochemical activity. Gangue- Clay minerals (commonly montmorillonite), carbonate minerals, glauconite, quartz, chert, and biogenic silica.

Carbonate-facies deposits: Ore- Rhodochrosite, kutnahorite, siderite, mixed manganese and iron carbonate minerals, pyrite, and wad. Gangue- Clay, calcium and calcium-magnesium carbonate minerals, glauconite, organic matter, pyrite, quartz, and biogenic silica.

Mineral characteristics

Rocks that host these deposits can include various textural features, including sedimentary laminae, sedimentary oolites and pisolites, and diagenetic botryoidal and vuggy textures, that probably do not affect the environmental signature of these deposits. Grain-size variation among deposits is extreme.

Secondary mineralogy

Secondary minerals include lithiophorite, nsutite, and wad. Nsutite and vernadite may be associated with electrochemical activity.

Topography, physiography

The topography and physiography of these deposits are variable, nondiagnostic, and have limited relation to geoenvironmental signatures. Nsutite deposits tend to be perched on ridges and plateaus.

Hydrology

These deposits exert little, if any, influence on the local hydrologic regime. Locally, manganese carbonate minerals are present only below the water table.

Mining and milling methods

These deposits are mined by both open-pit and underground methods. Mining and milling sedimentary manganese ore generate manganese-rich dust, which may be the major health risk associated with sedimentary manganese deposits (Matrone and others, 1977).

ENVIRONMENTAL SIGNATURES

Drainage signatures

The geochemistry of water draining sedimentary manganese deposits is directly related to and mimics the characteristics of individual deposits.

Metal mobility from solid mine wastes

Manganese is weakly to moderately mobile except under acidic (oxide- and carbonate-facies deposits) or reducing (oxide-facies deposits) conditions. Base metals (for example, lead) are less mobile when contained in oxide minerals.

Soil, sediment signatures prior to mining

Manganese commonly is concentrated in soil, to form supergene deposits, by secondary manganese mineral growth. High manganese-iron ratios are characteristic of soil associated with these deposits. Abundances of other elements, except those of aluminum and potassium (in lithiophorite), are depleted by these processes.

Potential environmental concerns associated with mineral processing

Processing ore from deposits of this type can yield manganese-rich dust and enhance dissolved manganese abundances. Manganese mineral dissolution is enhanced by acidification of carbonate-facies deposits and (or) reduction and acidification of oxide-facies deposit.

Smelter signatures

Manganese ore is not commonly smelted near mine sites.

Climate effects on environmental signatures

Varying climatic conditions probably have minimal influence on the environmental signature related to these deposits unless they cause the chemistry of natural water to have lower pH (as with acid rain) or Eh.

Geoenvironmental geophysics

Detailed gravity, seismic (Sklash and Jiwani, 1983), and electrical surveys aid tonnage estimates and delineation of

deposit geometry prior to mining; accordingly, estimates concerning the potential magnitude of air and water pollution that may be associated with ore extraction can be made. Magnetic surveys augment these techniques by enabling definition of hydrologic features, including cavities, faults, and aquitards, within and surrounding deposits. In favorable circumstances, resistivity, seismic velocity, and seismic reflectivity surveys may enable estimates of depth to the water table.

REFERENCES CITED

- Cannon, W.F., and Force, E.R., 1986, Descriptive model of sedimentary Mn: U.S. Geological Survey Bulletin 1693, p. 231.
- Cox, D.P. and Singer, D.A., 1986, Mineral Deposit Models: U.S. Geological Survey Bulletin 1693, 379 p.
- Dorr, J.V.N., II, Crittenden, M.D., Jr., and Worl, R.G., 1973, Manganese, *in* United States Mineral Resources: U.S. Geological Survey Professional Paper 820, p. 885-398.
- Force, E.R., and Cannon, W.F., 1988, Depositional model for shallow-marine manganese deposits around black-shale basins: *Economic Geology*, v. 83, p. 93-117.
- Force, E.R., Back, William, Spiker, E.C., and Knauth, L.P., 1986, A ground-water mixing model for the diagenesis of the Imini manganese deposit (Cretaceous) of Morocco: *Economic Geology*, v. 81, p. 65-79.
- Keller, G.V., 1989, Electrical properties, section V, *in* Carmichael, R.S., ed., *Practical Handbook of physical properties of rocks and minerals*, Boca Raton, CRC Press, p. 357-427.
- Matrone, G., Jenne, E.A., Kubota, J., Mena, I., and Newberne, P.M., 1977, Manganese, *in* Mertz, W., ed., *Geochemistry and the environment*, v. II, The relation of other selected trace elements to health and disease: National Academy of Sciences, p. 29-39.
- Mosier, D.L., 1986, Grade and tonnage model of sedimentary Mn: U.S. Geological Survey Bulletin 1693, p. 231-233.
- Pracejus, B., Bolton, B.R., and Frakes, L.A., 1986, Nature and development of supergene manganese deposits, Groote Eylandt, Northern Territory, Australia: *Ore Geology Reviews*, v. 4, p. 71-98.
- Rowston, D.L., 1965, Gravity survey of manganese deposits in the Mt. Sidney-Woodie-Woodie, Pilbara gold field: *Geological Survey of Western Australia Annual Report for 1964*, p. 49-51.
- Roy, Supriya, 1981, *Manganese deposits*: London, Academic Press, 458 p.
- Sangmor, S.S., Dorbor, J.K., Hoskins, L., Mason, J.A., Jr., Murray, G., and Pshoor, P., 1982, The Mt. Dorthrow manganese mineralization: Monrovia, Liberian Geological Survey, Project report of investigations, 1981, 53 p.
- Sapozhnikov, P.G., 1970, *Manganese deposits of the Soviet Union*: Jerusalem, Israel Program for Scientific Translations, 522 p.
- Sklash, M.G., and Jiwani, R.N., 1983, Groundwater contamination on Walpole Island, Ontario, Canada, *in* *Papers of the International conference on groundwater and man*, Volume 2, *Groundwater and the environment*: Australian Water Resources Council Conference Series, No. 8, p. 387-394.
- U.S. Geological Survey and Corporacion Venezolana de Guayana, Tecnica Minera, C.A., 1993, *Geology and mineral resource assessment of the Venezuelan Guayana Shield*: U.S. Geological Survey Bulletin 2062, 121 p.

**LOW SULFIDE AU QUARTZ VEINS
(MODEL 36a; Berger, 1986)**

by Richard J. Goldfarb, Byron R. Berger, Terry L. Klein, William J. Pickthorn, and Douglas P. Klein

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

These deposits consist of Archean through Tertiary quartz veins, primarily mined for their gold content, that generally contain no more than 2 to 3 volume percent sulfide minerals, mainly pyrite, in allochthonous terranes dominated by greenstone and turbidite sequences that have been metamorphosed to greenschist facies. Wall rocks contain abundant carbonate and sulfide minerals, quartz, and sericite. Arsenic and antimony are enriched in alteration haloes (fig. 1). These deposits are also known as mesothermal, Mother Lode-type, orogenic, metamorphic rock-hosted, greenstone gold (Archean), turbidite-hosted (Phanerozoic), and slate belt gold (Phanerozoic) deposits.

Low sulfide gold quartz veins in the United States are presently being mined and prospected within rocks of accreted lithotectonic terranes along both continental margins. Development of Paleozoic lode deposits in recent years has been restricted to the South Carolina part of the Carolina slate belt. Open pit mining of the more than 1.5 million oz of gold at the Ridgeway mine, the largest of the deposits, is continuing at a rate of about 100,000 oz/yr. In the Mother Lode region of central California, a few old mines have been reopened in the last 10 to 15 years as open pit operations. Each has been recovering 500,000 to 750,000 oz of gold from low-grade, Early Cretaceous deposits. Production from the Alaska-Juneau and Kensington Eocene vein deposits in southeastern Alaska by underground operations is scheduled to commence during the next few years and will yield about 6 million oz of gold. In the Alaskan interior, open-pit mining will eventually yield 4 million oz of gold from the mid-Cretaceous Fort Knox deposit.

Examples

Yilgarn Block, Western Australia; Abitibi Belt, Superior Province, Canada; Yellowknife, Northwest Territory, Canada; Bendigo/Ballarat, Victoria, Australia; Murantau, Uzbekistan; Mother Lode, Calif.; Juneau Gold Belt, Alaska; Otago Schist Belt, South Island, New Zealand.

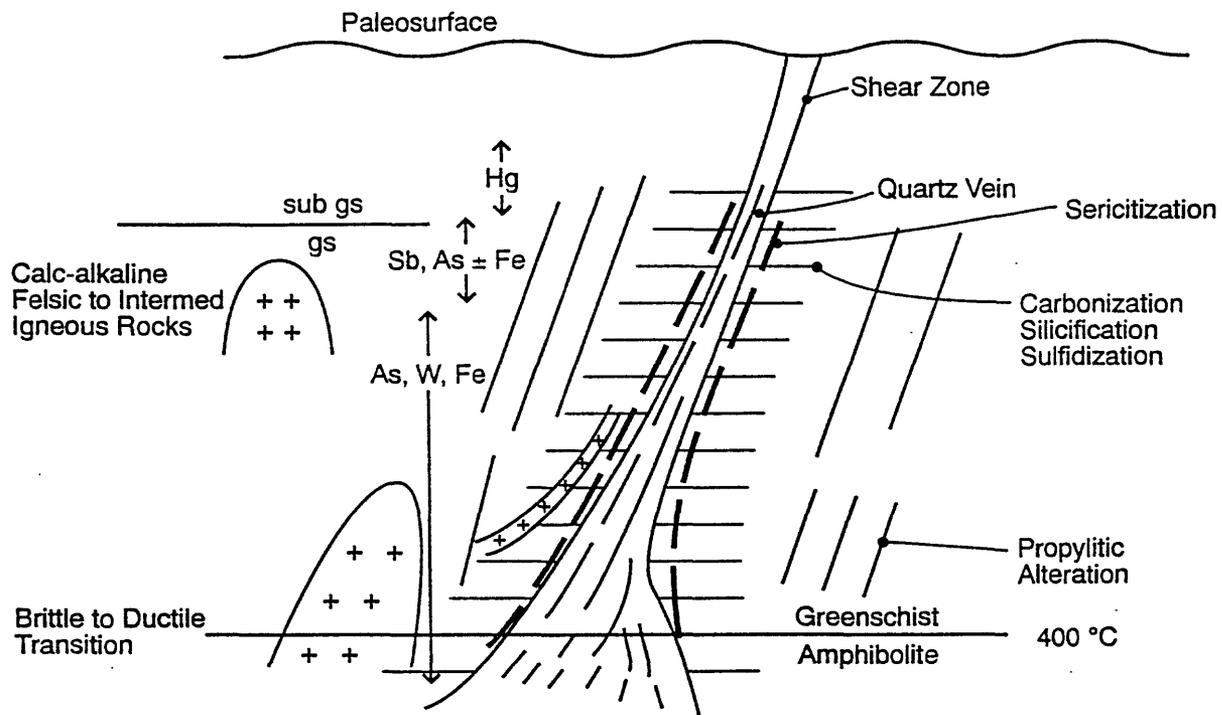


Figure 1. Schematic geologic cross section of a low-sulfide gold deposit.

Spatially and (or) genetically related deposit types

Associated deposit types (Cox and Singer, 1986) may include silica-carbonate mercury (Model 27c), and gold-antimony (Model 36c), which may reflect shallower exposures of similar hydrothermal systems in areas of limited erosion. In areas of extensive uplift and erosion, gold lodes are re-concentrated in extensive placer accumulations (Model 39a). Low sulfide gold quartz vein deposits subjected to tropical weathering can produce lateritic saprolite (eluvial placer) deposits (Model 38g; McKelvey, 1992). Much older, pre-accretionary Cyprus, Besshi, and Kuroko volcanogenic massive sulfide deposits (Models 24a, 24b, 28a) are spatially associated with gold veins in terranes that contain significant volumes of volcanic rock.

Potential environmental considerations

- (1) Moderate amounts of acid mine drainage may be present where local, relatively high sulfide mineral concentrations are present in gold ore, where broad zones of sulfidization characterize wall rocks, and (or) where much of the ore is hosted by greenstone that has relatively low acid-buffering capacity.
- (2) Oxidation of mine tailings that contain sulfide minerals, particularly arsenopyrite, or soil formed from unmined, yet sulfide-mineral-bearing rock can release potentially hazardous arsenate, arsenite, and methylarsenic species.
- (3) Increased concentrations of arsenic, antimony, and other trace metals may be present downstream from deposits. Cyanide used for gold extraction at many active mines is a potential additional contaminant in waste water discharge.
- (4) Mercury amalgamation carried out during historic operations may be a source of mercury contamination in aquatic life and in surface sediment. Continued use of mercury amalgamation and roasting for gold extraction in some parts of the world is a direct and very serious health hazard.
- (5) Disposal of tailings from developed deposits can cause sedimentation problems in adjacent waterways.
- (6) Modern open-pit mining methods, allowing for development of previously uneconomic, low-grade gold deposits pose quality-of-life concerns. Potential concerns include mining-related visual impacts, increased traffic and noise, and dust generation. Open-pit mining also produces significantly greater volumes of untreated waste rock.
- (7) Long term exposure to arsenic concentrated in tailings can cause cancer and kidney disease.

Exploration geophysics

Silicified rock, much of which corresponds to wall rock that contains abundant sulfide minerals, is commonly associated with local resistivity highs. Silicified rock and carbonate minerals along veins increase density and resistivity and may allow indirect sulfide mineral identification using detailed electromagnetic, direct current resistivity, and micro-gravity mapping. Disseminated pyrite, arsenopyrite, and chalcopyrite distributions can be outlined using induced polarization/resistivity surveys. Piezo-electricity may locate sulfide-mineral-bearing quartz veins. Host rocks that contain at least moderate amounts of magnetite may have associated magnetic lows due to magnetite destruction in alteration-halos.

References

Geology: Berger (1986), Bliss (1986, 1992), Groves and others (1989), Kerrich and Wyman (1990), Kontak and others (1990), Nesbitt (1991), Berger (1993), Goldfarb and others (1993), Phillips and Powell (1993), and Klein and Day (1994).
Environmental geology and geochemistry: Howell and others (1994), Callahan and others (1994), Cicutat and others (1994), Azcue and others (1995), and Trainor and others (in press).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Deposit size is extremely variable. Archean deposits-mean tonnage is 1.08 million metric tonnes; range is 0.004 to 199 million metric tonnes. The mean tonnage of Phanerozoic deposits is 0.03 million metric tonnes; range is 0.001 to 25 million metric tonnes. The mean tonnage of Chugach-type Phanerozoic deposits is 0.003 million metric tonnes; range is 0.001 to 0.07 million metric tonnes. Because of the high-grade nature of some veins (greater than 30 to 50 g gold/t), many low tonnage deposits (for instance, Chugach-type low sulfide gold deposits; Bliss, 1992) are developed by small, underground workings. Deposits that contain at least 0.5 to 5 million oz gold in low grade ore (generally 2 to 10 g gold/t) have been mined in large, more modern open-pit operations. The largest example of such a deposit is Murantau, Uzbekistan, which contains greater than 140 million oz gold (Berger and others, 1994).

Host rocks

Archean ore is largely hosted by metamorphosed basalt (greenstone), although ultramafic volcanic rocks (komatiite), felsic volcanic rocks, and granitoid intrusions are locally important hosts. Most of these deposits are in preserved cratonic blocks. Phanerozoic deposits are hosted in slate and graywacke in deformed, continental margin orogenic belts. Where competent, pre-ore igneous bodies are present in metasedimentary sequences, they commonly preferentially host vein-bearing fracture systems.

Surrounding geologic terrane

Deposits are restricted to medium-grade, generally greenschist facies, metamorphic rocks. High-tonnage deposits, exemplified by Murantau, Uzbekistan, have a spatial association with major structural zones that are commonly believed to be old terrane boundaries. Contemporaneous calc-alkaline dioritic to granitic plutons, sills, and batholiths within a few tens of kilometers of ore indicate that both are products of regional, middle to lower crustal thermal events.

Wall-rock alteration

Mineral phases vary with host rock lithology; halo width varies with size of hydrothermal system. Alteration zones are poorly developed in metasedimentary host rocks, but are broad and distinct in both felsic and mafic igneous rocks. Silicified rock and carbonate minerals are ubiquitous. Disseminated pyrite and (or) arsenopyrite consistently are present in these broad haloes. Sericite is common, but only close to discrete gold-bearing veins; in some systems, biotite is also present adjacent to veins. Sericite gives way to a chlorite-epidote propylitic zone distal to veins. Talc, chlorite, and fuchsite are also common in alteration zones within ultramafic host rocks; albite is common in granitoid host rocks. Wall rocks are notably enriched in H₂O, CO₂, S, K, Au, W, Sb, and As (Nesbitt, 1991).

Nature of ore

Ore may be present in quartz veins and (or) adjacent sulfidized wall rock. Gold is present as free grains in quartz, as blebs attached to wall rock ribbons, and in veinlets cutting sulfide grains. Individual veins are 1 to 10-m-wide discrete fissure fillings that have strike lengths of less than 100 m. Many veins show ribbon texture or, less commonly, contain brecciated wall rock fragments. In some deposits, ore forms dense stockworks of cm-wide veinlets. Vein swarms at the large deposits can attain 5-km strike lengths, 500 m widths, and extend 2 km down dip. Carbonate minerals may form either (1) restricted alteration zones that range from a few to tens of meters away from small shear zones or (2) may be abundant in rocks within several kilometers of major faults.

Deposit trace element geochemistry

Abundances of silver, arsenic, gold, and iron are consistently anomalous; tungsten and antimony abundances are much less consistently anomalous; bismuth, copper, mercury, lead, and zinc abundances are anomalous in many deposits; less commonly, anomalous amounts of tellurium and molybdenum are detected.

Ore and gangue mineralogy and zonation

- (1) Gold is present as native gold and electrum.
- (2) Potentially acid-generating sulfide minerals (in order of abundance) are pyrite, arsenopyrite > stibnite > chalcopyrite, pyrrhotite, galena, sphalerite > telluride minerals, tetrahedrite > bismuthinite > molybdenite.
- (3) Scheelite and graphite are common.
- (4) Potentially acid-buffering carbonate minerals include siderite, ankerite, calcite, magnesite, or ferroan dolomite; the composition of the carbonate species is a function of wall rock chemistry.
- (5) Silicate gangue minerals include quartz, muscovite, chlorite, biotite, fuchsite, tourmaline, rutile, albite, and (or) talc.
- (6) Zoning is uncommon; mineral assemblages and proportions are commonly consistent over depths of greater than 1,000 m. In some systems, shallow levels may contain more abundant stibnite or sulfosalt minerals and native silver (Berger, 1993). Deeper zones may be more pyrrhotite-rich.

Mineral characteristics

Sulfide minerals are usually present as finely disseminated grains in quartz and wall rocks. In some deposits, massive clots of arsenopyrite, as large as tens of cm, may be present locally. In rare examples, gold-bearing veins may contain massive stibnite (10 to 50 volume percent of the vein material) throughout the deposit (see Berger, 1993).

Secondary mineralogy

Secondary minerals are not common. Occasionally, some arsenopyrite has weathered to scorodite. Minor limonite is present in many veins.

Topography, physiography

The deposits do not form distinct topographic features although in some mining districts (for example, Bendigo, Australia) mineralized zones may form distinctive linear ridges. They may have been emplaced along steep and rapidly uplifting mountain belts; many pre-Tertiary low-sulfide gold-quartz veins are present in more tectonically stable zones of moderate relief.

Hydrology

Veins are generally hosted in permeable fracture zones and hence are also significant local ground water conduits. Mining relatively sulfide-mineral-rich veins of this deposit type could cause discharge of minor volumes of relatively metal-rich ground water. However, seepage from poorly consolidated tailings piles and adits at historic workings is likely to be the most common source of metal contamination of surface water near this type of gold deposit.

Mining and milling methods

Both underground and open pit mining methods are presently being used to extract ore. In the United States, except for southeastern Alaska, open pit mining is most common. During milling, ore is usually crushed and ground in a ball mill; subsequently, gravity concentration is used to remove the largest gold particles. Remaining ore is reground, classified and thickened, recycled through the gravity concentrator, and then processed in cyanide vats for 48 hours. The slurry is subsequently sent to a carbon-in-pulp circuit where dissolved gold is adsorbed on carbon. Gold is then stripped from carbon and electroplated on steel wool before being refined into bullion in a furnace. Alternatives to vat leaching during cyanidation include *in situ* and heap leaching.

In some parts of the world, mercury amalgamation is still being used to aid gold recovery. Sulfur compounds, which adversely impact the amalgamation process, are eliminated by first roasting ore. Mixing mercury with gold concentrates results in amalgam that leaves gold behind when the mercury is volatilized.

ENVIRONMENTAL SIGNATURES

Drainage signatures

For both mined and unmined orebodies, low sulfide mineral contents of ore and acid-buffering capacity of widespread carbonate alteration assemblages generally prevent significant acid-mine drainage and heavy metal contamination associated with this deposit type.

Natural drainage: Limited data (Carrick and Maurer, 1994; Cieutat and others, 1994; Trainor and others, in press) suggest that unmined occurrences have little impact on surface water pH or trace element content. In southern Alaska, data indicate that arsenic abundances increase from <5 to 6 $\mu\text{g/l}$, iron from <20 to 140 $\mu\text{g/l}$, and sulfate from <2 to 3 to 5 mg/l where natural water encounters unmined low-sulfide gold quartz vein occurrences.

Mine drainage: Arsenic and iron abundances in water draining small workings may be enhanced by one to two orders-of-magnitude relative to background abundances downstream from unmined occurrences (Cieutat and others, 1994; Trainor and others, in press). Other metals do not exhibit corresponding enrichments. Even water draining directly from major pits and extensive underground workings can have neutral pH and low metal contents; water draining the Alaska-Juneau pit and underground workings, Alaska's largest gold mine, contain <6 $\mu\text{g/l}$ arsenic and <100 $\mu\text{g/l}$ iron at a pH of 8.0; sulfate abundances in this water are as much as 340 mg/l (Echo Bay Mines, unpub. company data). Water flowing out the portal of the Independence, Alaska, mine in the Willow Creek district, the fourth largest past lode gold producer in the state, has a pH of 7.8 and contains <40 $\mu\text{g/l}$ iron, 37 $\mu\text{g/l}$ arsenic, and <4 $\mu\text{g/l}$ cadmium, copper, lead, antimony, tungsten, and zinc (R.J. Goldfarb, unpub. data, 1995).

In rare examples, locally high concentrations of sulfide minerals can lead to significant metal-rich and (or) acid mine drainage. Contaminated water that drained from an old adit at the site of an open pit gold mine at Macraes Flat, South Island, New Zealand, which had a pH of 2.9 and elevated dissolved metal abundances, including as much as 77 mg/l zinc and 80 mg/l iron (BHP Gold, New Zealand, unpub. company report, 1988), may reflect this type of situation.

Seepage from poorly consolidated tailings piles may be more acidic. Small volumes of water seeping from tailings in the Cariboo district, British Columbia has a pH of 2.7 and contains 556 $\mu\text{g/l}$ arsenic and elevated abundances of cadmium, copper, lead, and zinc (Azcue and others, 1995). Seepage from sulfide mineral concentrates at an abandoned mill site, of the Treadwell, southeastern Alaska, mines has a pH of 2.9 and contains 330 mg/l iron,

2500 $\mu\text{g/l}$ zinc, 380 $\mu\text{g/l}$ copper, 160 $\mu\text{g/l}$ cobalt, 100 $\mu\text{g/l}$ nickel, 32 $\mu\text{g/l}$ cobalt, and 21 $\mu\text{g/l}$ lead (R.J. Goldfarb, unpub. data, 1995).

Mercury, which is used for gold extraction, is extremely enriched in sediment and fish tissue in drainages downstream from many historic low-sulfide gold mines (Callahan and others, 1994). Down-river from present-day gold mines in Brazil, mercury abundances are as much as 20 ppm in sediment, 2.7 ppm in fish, and 8.6 $\mu\text{g/l}$ in water (Pfeiffer and others, 1989). Down-river from the California Mother lode veins, dredged river sediment contains as much as 37.5 ppm mercury and surface and ground water contains 13 to 300 $\mu\text{g/l}$ mercury (Prokopovich, 1984). Extreme mercury abundances have been documented in sediment in drainages of the Carolina slate belt and the Dolgellau gold belt, Wales, more than 75 years after cessation of mining (Fuge and others, 1992; Callahan and others, 1994). Unfiltered and filtered samples of water draining tailings piles in the Fairbanks, Alaska, district contain as much as 0.58 and 0.11 $\mu\text{g/l}$ mercury, respectively (R.J. Goldfarb, unpub. data, 1995).

Metal mobility from solid mine wastes

Acid mine drainage problems are probably restricted to water that infiltrates untreated mine dump piles. In temperate climates, initial spring snow melt draining dumps is likely to contain significant heavy metal abundances, including arsenic, iron, and antimony, and less commonly lead and zinc, mainly due to dissolution of soluble salts accumulated during winter. In most cases, small volume acidic effluent seeping from waste piles is diluted to background abundances upon entering adjacent stream channels; consequently, environmental impact is restricted to surface channels upstream from their intersections with the nearest, major surface waterway.

Arsenic is usually the trace element of greatest environmental concern in soil associated with mine tailings. Inadvertent soil ingestion by young children and arsenic-rich household dust pose potential risks to human health. These risks have become serious public issues in parts of the California Mother Lode belt where housing projects have been developed on soil derived from old mine tailings (Time, September 25, 1995, p. 36). Secondary, arsenic-bearing salt minerals, and to a lesser extent, relatively insoluble arsenic-bearing sulfide minerals, become bioavailable primarily by adsorption from the fluid phase in the small intestine. Geochemical factors that control arsenic bioavailability from soil include the type of arsenic-bearing mineral, the degree of encapsulation of that mineral in an insoluble matrix, the nature of alteration rinds on mineral grains, and the rate of arsenic dissolution in the gastrointestinal tract (Davis and others, 1992).

Soil, sediment signatures prior to mining

Arsenic concentrations in soil and sediment are about 50-1,000 ppm near unmined deposits; background abundances elsewhere are typically 10-40 ppm. Antimony levels are commonly >5 ppm near deposits, whereas they are normally <2 ppm in areas unaffected by hydrothermal activity (Bowell and others, 1994; R.J. Goldfarb, unpub. data, 1995).

Potential environmental concerns associated with mineral processing

Summarized from Ripley and others (1995).

- (1) Mercury amalgamation, commonly used in historic gold extraction processes, may have deposited significant amounts of mercury in tailings piles. Where amalgamation is still used, volatilized mercury generated by the process may significantly affect air quality because as much as ten percent of the mercury used is lost to the atmosphere.
- (2) Most cyanide used for gold extraction is recovered and recycled, but some inevitably remains in tailings liquor and can leak into regional ground water networks. Any loss of cyanide to the environment is a major concern because it is toxic to a wide variety of organisms. Many mills now use chemical-treatment systems to convert hazardous cyanide compounds to insoluble compounds that are not bioavailable. This is especially critical in cold climates where natural volatilization of cyanide from holding ponds is relatively slow.
- (3) Where heap-leaching methods are employed, environmental risks are greater. Leakage and erosion risks are greatly increased, as are risks to wildlife, because cyanide leaching is usually done outdoors. *In situ* leaching, if applied to relatively impermeable orebodies, could result in local aquifer contamination.
- (4) Roasting ore that contains abundant sulfide minerals emits significant amounts of arsenic trioxide and other metal oxides into the atmosphere.
- (5) Highly acidic effluent is produced during sulfide bio-oxidation. Without proper neutralization or during spills, this effluent can be extremely hazardous.
- (6) Crushing and grinding ore may present noise and dust hazards.

Smelter signatures

Ore derived from these deposits is not smelted.

Climate effects on environmental signatures

In dry and seasonally wet climates, the potential for generating small-volume pulses of significantly metal-enriched acid mine drainage is enhanced by evaporation and soluble salt accumulation. In wet climates, increased surface runoff enhances dilution and may mitigate peak acid and heavy-metal concentrations that characterize mine drainage in dry and seasonally wet climates.

Geoenvironmental geophysics

Wide-band electromagnetic systems can be used to identify major shears associated with veins that may serve as major ground water conduits. Direct current and electromagnetic resistivity and magnetic surveys can be used to study porous rock associated with faults and shear zones that may control ground water flow. Within and downslope from mine areas, low-resistivity acid- or metal-bearing water can be identified with electromagnetic or direct current induced polarization/resistivity surveys and ground penetrating radar. Structural and stratigraphic features such as bedrock topography, buried channels, and aquitards that affect water flow away from mine areas may be studied with electromagnetic or direct current resistivity, seismic refraction, and gravity surveys. Stratigraphic details in shallow sand and gravel water pathways can be investigated with seismic reflection and ground penetrating radar. Water flow may be monitored using self potential.

REFERENCES CITED

- Azcue, J.M., Mudroch, A., Rosa, F., Hall, G.E.M., Jackson, T.A., and Reynoldson, T., 1995, Trace elements in water, sediments, porewater, and biota polluted by tailings from an abandoned gold mine in British Columbia, Canada: *Journal of Geochemical Exploration*, v. 52, p. 25-34.
- Berger, B.R., 1986, Descriptive model of low-sulfide Au-quartz veins, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 239.
- Berger, B.R., Drew, L.J., Goldfarb, R.J., and Snee, L.W., 1994, An epoch of gold riches-the Late Paleozoic in Uzbekistan, central Asia: *Society of Economic Geologists Newsletter*, no. 16, p. 1, 7-11.
- Berger, V.I., 1993, Descriptive and grade and tonnage model for gold-antimony deposits: U.S. Geological Survey Open-File Report 93-194, 24 p.
- Bliss, J.D., 1986, Grade and tonnage model of low-sulfide Au-quartz veins, *in* Cox, D.P., and Singer, D.A., eds., *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, p. 239-243.
- _____, 1992, Grade and tonnage model of Chugach-type low-sulfide Au-quartz veins, *in* Bliss, J.D., ed., *Developments in mineral deposit modelling: U.S. Geological Survey Bulletin 2004*, p. 44-46.
- Bowell, R.J., Morley, N.H., and Din, V.K., 1994, Arsenic speciation in soil porewaters from the Shanti mine, Ghana: *Applied Geochemistry*, v. 9, p. 15-22.
- Callahan, J.E., Miller, J.W., and Craig, J.R., 1994, Mercury pollution as a result of gold extraction in North Carolina, U.S.A.: *Applied Geochemistry*, v. 9, p. 235-241.
- Carrick, S., and Maurer, M., 1994, Preliminary water resource assessment of the Girdwood area, Alaska: Alaska Division of Geological and Geophysical Surveys, Public Data File 94-51, 36 p.
- Cieutat, B.A., Goldfarb, R.J., Borden, J.C., McHugh, J., and Taylor, C.D., 1994, Environmental geochemistry of mesothermal gold deposits, Kenai Fjords National Park, south-central Alaska, *in* Till, A.B., and Moore, T., eds., *Geological Studies in Alaska by the U.S. Geological Survey, 1993: U.S. Geological Survey Bulletin 2107*, p. 21-25.
- Cox, D.P., and Singer, D.A., eds., 1986, *Mineral deposit models: U.S. Geological Survey Bulletin 1693*, 379 p.
- Davis, A., Ruby, M.V., and Bergstrom, P.D., 1992, Bioavailability of arsenic and lead in soils from the Butte, Montana mining district: *Environmental Science Technology*, v. 26, p. 461-468.
- Fuge, R., Pearce, N.J.G., and Perkins, W.T., 1992, Mercury and gold pollution: *Nature*, v. 357, p. 369.
- Goldfarb, R.J., Snee, L.W., and Pickthorn, W.J., 1993, Orogenesis, high-T thermal events, and gold vein formation within metamorphic rocks of the Alaskan Cordillera: *Mineralogical Magazine*, v. 57, p. 375-394.
- Groves, D.I., Barley, M.E., and Ho, S.E., 1989, Nature, genesis and tectonic setting of mesothermal gold mineralization in the Yilgarn block, Western Australia, *in* Keays, R.R., Ramsey, W.R.H., and Groves, D.I., eds., *The geology of gold deposits--The perspective in 1988: Economic Geology Monograph 6*, p. 71-85.
- Kerrick, R., and Wyman, D., 1990, Geodynamic setting of mesothermal gold deposits--An association with accretionary regimes: *Geology*, v. 18, p. 882-885.

- Klein, T.L., and Day, W.C., 1994, Descriptive and grade-tonnage models of Archean low-sulfide Au-quartz veins and a revised grade-tonnage model of Homestake Au: U.S. Geological Survey Open-File Report 94-250, 29 p.
- Kontak, D.J., Smith, P.K., Kerrich, R., and Williams, P.F., 1990, Integrated model for Meguma Group lode gold deposits, Nova Scotia, Canada: *Geology*, v. 18, p. 238-242.
- McKelvey, G.E., 1992, Descriptive model of laterite-saprolite Au, *in* Bliss, J.D., ed., *Developments in mineral deposit modelling*: U.S. Geological Survey Bulletin 2004, p. 47-49.
- Nesbitt, B.E., 1991, Phanerozoic gold deposits in tectonically active continental margins, *in* Foster, R.P., ed., *Gold metallogeny and exploration*: Blackie, London, p. 104-132.
- Pfeiffer, W.C., DeLacerda, L.D., Malm, O., Souza, M.M., DaSilveira, E.G., and Bastos, W.R., 1989, Mercury concentrations in inland waters of gold-mining areas of Rondonia, Brazil: *The Science of the Total Environment*, v. 87-88, p. 233-240.
- Phillips, G.N., and Powell, R., 1993, A link between gold provinces: *Economic Geology*, v. 88, p. 1084-1098.
- Prokopovich, N.P., 1984, Occurrence of mercury in dredge tailings near Folsom South Canal, California: *Bulletin of the Association of Engineering Geology*, XXI, p. 531-543.
- Ripley, E.A., Redmann, R.E., and Crauder, A.A., 1995, *Environmental effects of mining*: Delray Beach, Florida, St. Lucie Press, 356 p.
- Trainor, T.P., Fleisher, S., Wildeman, T.R., Goldfarb, R.J., and Huber, C., in press, Environmental geochemistry of the McKinley Lake gold district, Chugach National Forest, Alaska, *in* Moore, T., and Dumoulin, J.D., eds., *Geological Studies in Alaska by the U.S. Geological Survey, 1994*: U.S. Geological Survey Bulletin 2152.

STRATABOUND AU IN IRON-FORMATIONS (MODEL 36b; Berger, 1986)

by Ed DeWitt, William D. Heran, and M. Dean Kleinkopf

SUMMARY OF RELEVANT GEOLOGIC, GEOENVIRONMENTAL, AND GEOPHYSICAL INFORMATION

Deposit geology

Deposits are concentrations of electrum and the sulfide minerals troilite, pyrrhotite, pyrite, and arsenopyrite, and include electrum in carbonate-facies iron-formations, and are mined for gold and silver. Notably lacking are base-metal sulfide minerals. Bed-controlled ore predominates; subsequent regional metamorphism of stratabound deposits can result in ore redistribution and concentration in quartz vein-related deposits.

Most large gold deposits in iron-formation (GDIF) are strata-bound, bed-controlled concentrations of sulfide minerals and gold that were probably formed by syngenetic, hot-spring processes during deposition of iron-formation. Iron-formation and layered, bed-controlled sulfide mineral deposits were deposited on the seafloor under extremely reducing conditions, in an environment that contained abundant organic carbon and iron and variable amounts of sulfur. Gold abundances are highly correlated with either those of pyrrhotite and troilite or with that of arsenopyrite, depending on the physical-chemical conditions of hot-spring activity. Obvious feeder zones and alteration halos within GDIF are not known.

Subsequent regional metamorphism of most GDIF has generated, *in situ*, quartz veins that may locally reconcentrate gold within iron-formation. Mobility of gold and sulfide minerals during regional metamorphism is normally restricted to the immediate thickness of the iron-formation. Quartz veins contain very few sulfide minerals, but do contain visible electrum and have selvages rich in pyrrhotite, chlorite, pyrite, ankerite, and electrum. Arsenopyrite may or may not be present in vein selvages. Because veins developed during regional metamorphism, they may be deformed or they may post-date the last folding event. Available evidence indicates that fluids responsible for quartz vein generation were not transported into the iron-formation from external sources.

The Homestake Mine produces about 350,000 ounces of gold each year, which makes it one of the five largest individual gold mines in the United States. Until the late 1980s, Homestake produced more gold than any other mine in the western hemisphere.

Examples

Homestake, S. Dak.; Jardine, Mont.; Lupine, Northwest Territories; São Bento, Brazil; Cuiaba, Brazil; Champion, India.

Spatially and (or) genetically related deposit types

Morro Velho, Brazil, may be a spatially related deposit, but data necessary to evaluate this possibility are incomplete.

Potential environmental considerations

The two mining operations in the United States that exploit examples of this deposit type, Homestake, S. Dak., and Jardine, Mont., comply with existing state, federal, and local environmental regulations. They pose no potential environmental risks.

Exploration geophysics

Oxide-facies iron-formation has high magnetization and density; consequently, its presence can commonly be delineated by aeromagnetic and gravity studies (Kleinkopf and Redden, 1975; Hildenbrand and Kucks, 1985). However, carbonate-facies iron-formation that hosts these gold deposits commonly contains no magnetite and is weakly magnetic, except where it contains abundant pyrrhotite. In carbonate-facies iron-formation, aeromagnetic highs are best developed in association with pyrrhotite- or troilite-rich deposits. Ground magnetic surveys have been used to delineate oxide-facies iron-formation and predict strike extensions, bed thickness, and dip of magnetic zones within stratigraphic sequences (Lindeman, 1984). Induced polarization and a variety of electromagnetic surveys, which can help identify concentrations of disseminated, conducting minerals, can be used to refine the location of disseminated, sulfide-mineral bearing deposits and to project the extent of known deposits (Lindeman, 1984). Potential host rocks that contain iron oxide and carbonate minerals can be identified with high resolution imaging spectrometers where vegetation does not obscure rock reflectance characteristics (Clark and others, 1990).

References

Rye and others (1974), Rye and Rye (1974), Bidgood (1978), Hallager (1980), Ladeira (1980), Kath (1990), Caddey and others (1991), and Kerswill (1993).

GEOLOGIC FACTORS THAT INFLUENCE POTENTIAL ENVIRONMENTAL EFFECTS

Deposit size

Deposits mined in the past and those currently being mined range from as small as several hundred metric tons to 150 million metric tons.

Host rocks

Most GDIF are contained within carbonate-facies iron-formation or their metamorphosed equivalents. Oxide-facies iron-formations host very few gold deposits. Minor amounts of silicate-facies and oxide facies iron-formation are known. Host iron-formation may or may not be laterally continuous within the shale-dominant sedimentary sequence. Transitions within iron-formation from one facies to another are known, and range from carbonate- to oxide-, silicate-, and sulfide-facies. Typically, the iron-formations are less than 30 meters thick but quite continuous along strike. Minor tuffaceous rocks are associated with some iron-formation, but this component does not appear to be a prerequisite for GDIF. Clay-rich layers in the iron-formation may have formed by submarine weathering of basaltic material or direct hydrothermal precipitation of iron-rich material.

Surrounding geologic terrane

Iron-formation is most commonly developed within shale and graywacke terrane. Gold deposits within iron-formations (GDIF) are commonly restricted to epicratonic basins formed within foundered Archean or Proterozoic cratons. Deposits are typically contained within shale-dominated environments that lack volcanic input. A few small deposits are within relatively high energy environments typified by graywacke. Arc-related rocks are unknown in environments that contain GDIF, as are very high-energy sedimentary rocks such as conglomerate, sandstone, and breccia. A slowly subsiding, continually rifting, epicratonic basin setting appears most favorable for GDIF genesis. Underlying and overlying contacts with shale-dominant rocks are transitional over distances of less than 10 m.

Wall-rock alteration

No wall-rock alteration is associated with bedded ore. Chloritization is associated with vein-related ore.

Nature of ore

Typical bedded ore contains 1 to 15 volume percent sulfide minerals, including troilite, pyrrhotite, pyrite, arsenopyrite. Electrum is associated with various sulfide minerals. Ore may be pyrrhotite rich, pyrite rich, or arsenopyrite rich. Typical quartz vein ore contains 0.5 to 10 volume percent sulfide minerals, including pyrrhotite, pyrite, and arsenopyrite. Electrum is again associated with various sulfide minerals or with quartz.

Deposit trace element geochemistry

Relative to underlying and overlying shale and graywacke, deposits are enriched in iron (in carbonate and sulfide minerals), carbon dioxide (in carbonate minerals), gold and silver (in electrum), and may or may not be enriched in arsenic (in arsenopyrite and loellingite).

Ore and gangue mineralogy and zonation

Bedded ore contains the above-mentioned sulfide minerals and electrum within strata of siderite, ankerite, quartz, chlorite, biotite, and stilpnomelane. Quartz-vein ore contains pyrrhotite, pyrite, electrum, and may or may not contain arsenopyrite within veins or marginal to veins. Common gangue minerals associated with veins include quartz, chlorite, biotite, calcite, and ankerite. Silicate-facies iron-formation contains additional phyllosilicate minerals; metamorphism at higher grade conditions yields iron-formation that contains orthoamphibole and pyroxene-group minerals. Sulfide-facies minerals are commonly troilite and varieties of FeS more iron-rich than troilite, pyrrhotite, arsenopyrite, and pyrite, as well as electrum. Pyrrhotite and troilite are more abundant than pyrite and arsenopyrite, but the latter minerals can be highly concentrated in certain parts of GDIF.

Mineral characteristics

Pyrrhotite and troilite in non-metamorphosed, bed-controlled ore are fine-grained to very fine-grained.

Metamorphism of GDIF increases grain size to medium grained. Arsenopyrite and pyrite in non-metamorphosed, bed-controlled ore are coarser (medium-grained) than pyrrhotite and troilite. Metamorphism of pyrite and arsenopyrite does not increase their grain size. Electrum in bed-controlled ore may form very fine-grained inclusions in either pyrrhotite or arsenopyrite. Elemental gold and silver are also present in solid substitution for iron in arsenopyrite. Quartz-vein-controlled sulfide minerals are notably coarser grained than those in bed-controlled ore. Arsenopyrite and pyrrhotite in vein-controlled ore are commonly coarse-grained. Electrum in vein-controlled ore may be visible to fine-grained.

Secondary mineralogy

Surface weathering of all minerals is highly dependent on local climate. Weathering of siderite, ankerite, and calcite typically produces pits filled with iron oxide minerals. Weathering of pyrrhotite and arsenopyrite typically results in tarnished grains that are partially replaced by pyrite. Carbonate minerals in GDIF are highly capable of buffering oxidation reactions due to surface weathering.

Topography, physiography

Deposits are in desert, steppe, temperate forest, tundra, and tropical forest areas. Carbonate-rich rocks weather differently in each terrane, from prominent ridges in deserts to topographically low areas in tropical environments.

Hydrology

Water flow through metamorphic rocks is typically controlled by shear zones and fractures. Porosity of all host rocks is very low to nonexistent. Hydrologic flow models probably are not relevant for GDIF. Most existing deposits are exploited in underground mines that have complex dewatering systems and sophisticated water treatment plants.

Mining and milling methods

Open-pit mining is minor. Most deposits are exploited by underground mining involving block-caving, vertical crater retreat, small width stoping, or a combination of these techniques. Milling commonly involves gravity concentration and carbon-in-pulp extraction. Various specific metallurgical techniques are applied to specific ore types.

ENVIRONMENTAL SIGNATURES

Drainage signatures

Very few or no GDIF in the United States are contained in drainage basins that have only iron-formation-type deposits. Homestake, S. Dak., is surrounded by Tertiary, epithermal vein and replacement deposits that contribute metals to the drainage basin of Whitewood Creek. Jardine, Mont., is in an area covered by extensive Tertiary volcanic rocks; contributions from minor vein deposits in the Bear Creek drainage at Jardine may obscure the geochemical signatures attributable to Jardine. Metal contributions from the Yellowstone area hot springs above Jardine probably also overprint drainage signatures from the GDIF below Jardine.

Deposits in the Northwest Territories, Canada, are probably the best candidates for accurate definition of drainage signatures associated with GDIF, but topography, and therefore drainage net development, is negligible near Lupine and surrounding deposits. Soil geochemistry surrounding these deposits might accurately reflect pre-mining conditions, as the deposits were discovered in the early 1960s.

Metal mobility from solid mine wastes

Most mine waste is used for fill in underground mines. Open-pit dumps typically contain shale and graywacke that pose no environmental problems. Tailings of operating mines are contained within ponds that comply with federal, state, and local environmental regulations. Because ore contains no base metals and extraction of sulfide minerals during ore processing is extremely efficient, modern tailings contain virtually no metals that might pose environmental problems. Depending on the type of ore processing technique used, tailings may or may not contain sodium cyanide in dilute concentrations. Gold is routinely extracted from these solutions during the life of the tailings pond. Monitoring equipment is installed to ensure no adverse environmental effects.

Soil, sediment signatures prior to mining

Soil is probably enriched in iron, gold, and carbon dioxide; soil may be enriched in arsenic. No data applicable to definition of pre-mining soil geochemistry are available for deposits in the United States. Deposits in the Northwest Territories, Canada, are probably the best candidates for accurate definition of pre-mining soil geochemistry in an

Arctic environment, as these deposits were not discovered until the 1960s. Similarly, newly discovered deposits in the Amazon region of Brazil could be utilized to define pre-mining conditions in a tropical environment.

Potential environmental concerns associated with mineral processing

Currently operating mines comply with federal, state, and local environmental regulations. Details of some mineral processing techniques are confidential; state regulatory boards may have information on patented techniques.

Smelter signatures

No currently operating mines use smelters to process ore. Historic smelters may or may not have been numerous in different districts, depending on the number of individual mines. Smelters undoubtedly serviced many types of ore deposits, not only those from GDIF. Soil contamination from any one or group of smelters is not directly attributable to any one GDIF deposit.

Climate effects on environmental signatures

Deposits are found in climates ranging from tropical to tundra. The effects of various climatic regimes on the geoenvironmental signature specific to stratabound gold deposits are not known. Although deposits in areas of higher precipitation have enhanced potential for associated acid mine drainage, the low base-metal sulfide content of these deposits inhibits the development of significantly metal-enriched water.

Geoenvironmental geophysics

Detailed magnetic and electromagnetic surveys can delineate fluid migration paths along geologic contacts, faults, and fractures (Paterson, 1995) but application of these techniques in crystalline rocks can be difficult. Electrical and electromagnetic surveys can be used to trace and monitor acidic, metal-enriched ground water plumes (Ebraheem and others, 1990; McNeill, 1990) in horizontally stratified rocks, but with difficulty in crystalline terranes. Hot spots in tailings piles that result from ongoing redox reactions can be located using self potential methods. Induced polarization surveys can be used to discriminate between environmentally benign electrical conductors, such as clay bodies, and metal-enriched ground water (Paterson, 1995).

REFERENCES CITED

- Berger, B.R., 1986, Descriptive model of Homestake Au, *in* Cox, D.P., and Singer, D.A., eds., Mineral deposit models: U.S. Geological Survey Bulletin 1693, p. 244.
- Bidgood, T.W., 1978, Petrography and trace element distribution across a gold ore body in the Homestake Mine, Lead, South Dakota: Rapid City, South Dakota School of Mines and Technology, M.S. thesis, 97 p.
- Caddey, S.W., Bachman, R.L., Campbell, T.J., Reid, R.R., and Otto, R.P., 1991, The Homestake gold mine, an Early Proterozoic iron-formation-hosted gold deposit, Lawrence County, South Dakota, *in* Shawe, D.R., and Ashley, R.P., eds., Geology and resources of gold in the United States: U.S. Geological Survey Bulletin 1857-J, p. J1-J67.
- Clark, R.N., Gallagher, A.J., and Swayze, G.A., 1990, Material absorption band depth mapping of imaging spectrometer data using a complete band shape least-squares fit with library reference spectra: Proceedings of the Second Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) Workshop, JPL Publication 90-54, p. 176-186.
- Ebraheem, A.M., Hamburger, M.W., Bayless, E.R., and Krothe, N.C., 1990, A study of acid mine drainage using earth resistivity measurements: *Groundwater*, v. 28, no. 3, p. 361-368.
- Hallager, W.S., 1980, Geology of Archean gold-bearing metasediments near Jardine, Montana: Berkeley, University of California, Ph.D. dissertation, 136 p.
- Hildenbrand, T.G., and Kucks, R.P., 1985, Model of geothermal systems in southwestern South Dakota from gravity and aeromagnetic studies, *in* Hinze, W.J., ed., The Utility of Regional Gravity and Magnetic Anomaly Maps: Society of Exploration Geophysicists, p. 233-247.
- Kath, R.L., 1990, Mineralogy and petrology of the Homestake iron-formation and adjacent pelitic rocks, Lead, South Dakota; conditions and assemblages of metamorphism, P-T paths, fluid evolution, and gold mineralization: Rapid City, South Dakota School of Mines and Technology, Ph.D. thesis, 228 p.
- Kerswill, J.A., 1993, Models for iron-formation-hosted gold deposits, *in* Kirkham, R.V., Sinclair, W.D., Thorpe, R.I., and Duke, J.M., eds., Mineral Deposit Modeling: Geological Association of Canada, Special Paper 40, p. 171-199.

- Kleinkopf, M.D., and Redden, J.A., 1975, Bouguer gravity, aeromagnetic, and generalized geologic map of part of the Black Hills of South Dakota and Wyoming: U.S. Geological Survey Geophysical Investigations Map and Text, GP-903, scale 1:250,000.
- Ladeira, E.A., 1980, Metallogenesis of gold at the Morro Velho Mine and in the Nova Lima district, Quadrilátero Ferrífero, Minas Gerais, Brazil: London, Ontario, University of Western Ontario, Ph.D. dissertation, 272 p.
- Lindeman, F.W., 1984, Geophysical case history of Water Tank Hill--Mt. Magnet, W.A., *in* Doyle, H.A., ed., Geophysical Exploration for Precambrian Gold Deposits: University of Western Australia, 10, p. 97-112.
- McNeill, J.D., 1990, Use of electromagnetic methods for groundwater studies, *in* Ward, S.H., ed., Geotechnical and Environmental Geophysics, vol. 1: Review and Tutorial, Tulsa, Okla.: Society of Exploration Geophysics, p. 191-218.
- Paterson, N., 1995, Application of geophysical methods to the detection and monitoring of acid mine drainage, *in* Bell, R.S., ed., Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems, April 23-26, 1995, Orlando, Florida: Environmental and Engineering Geophysical Society, p. 181-189.
- Rye, C.M., Doe, B.R., and Delevaux, M.H., 1974, Homestake gold mine, South Dakota; 2. Lead isotopes, mineralization ages, and source of lead in ores of the northern Black Hills: *Economic Geology*, v. 69, p. 814-822.
- Rye, D.M., and Rye, R.O., 1974, Homestake Gold Mine, South Dakota; 1. Stable isotope studies: *Economic Geology*, v. 69, p. 293-317.