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Preliminary compilation of descriptive geoenvironmental mineral deposit models

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GEOENVIRONMENTAL MODELS OF MINERAL DEPOSITS--FUNDAMENTALS AND APPLICATIONS

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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 (chalcanthite, 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

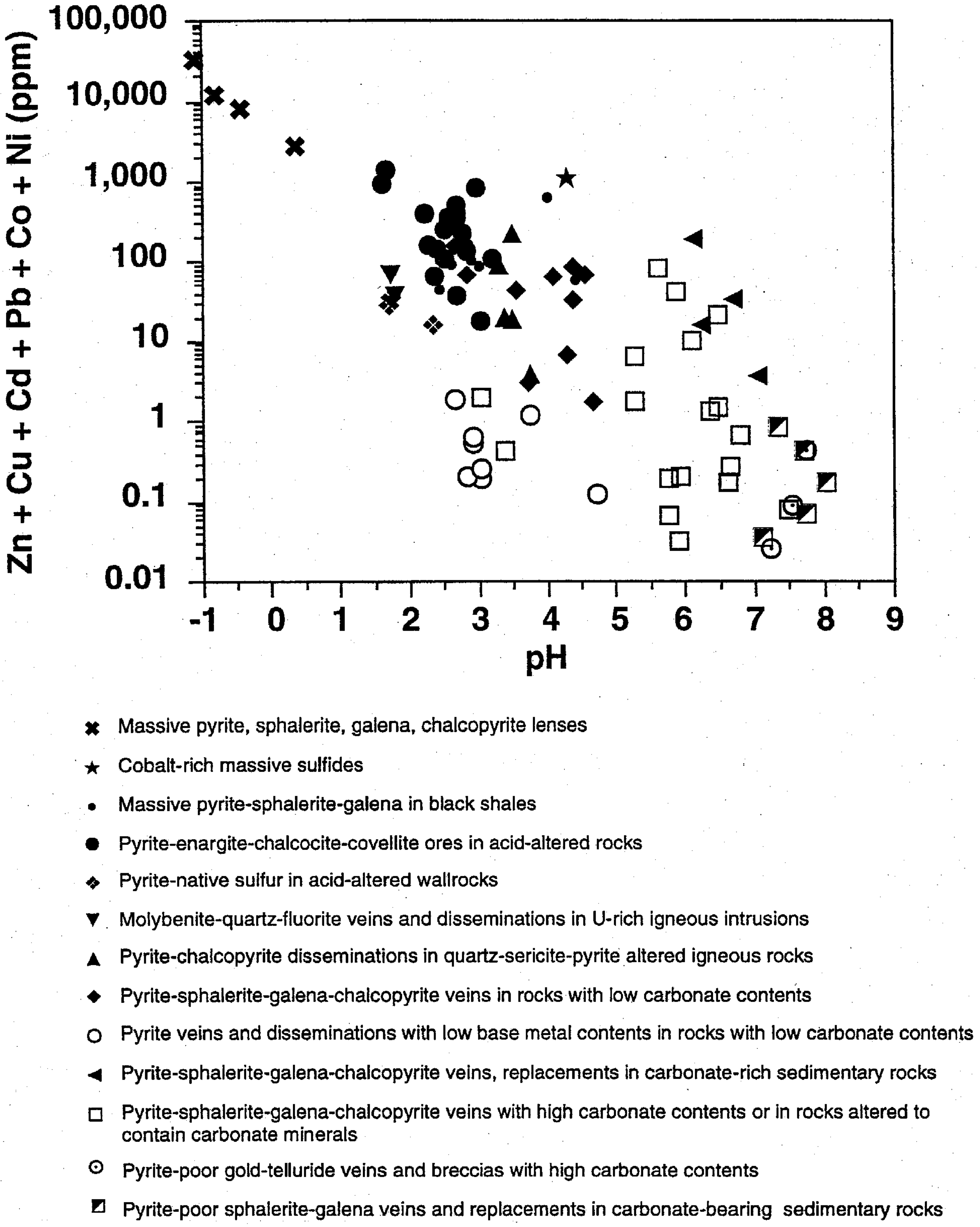

Figure 1. Variations in aqueous base metal concentrations (given as the sum of base metals base metals zinc, copper, cadmium, cobalt, nickel, and lead) as a function of pH for water draining various types of mineralized rock in diverse sites within Colorado.

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.