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GEOENVIRONMENTAL MODELS OF MINERAL DEPOSITS, AND GEOLOGY-BASED MINERAL-ENVIRONMENTAL ASSESSMENTS OF PUBLIC LANDS

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Geoenvironmental Models of Mineral Deposits, and Geology-Based Mineral-Environmental Assessments of Public Lands

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A detailed understanding of mineral deposit geology and geochemical processes, which control element dispersion into the environment, is crucial for the effective prediction, mitigation, and remediation of the environmental effects of mineral resource development. This paper describes (1) how geologic and geochemical information is being used at the USGS to develop environmental geology and geochemistry models of diverse mineral deposit types, and (2) how such models can be used by regulators, land managers, and industry to assess the past, present, and potential future environmental effects of of mineral-resource development.

Important controls on the environmental behavior of mineral deposits

The environmental behavior of mineral deposits is defined as the suites, concentrations, residences, and availabilities of chemical elements in soils, sediments, airborne particulates, and waters that result from the natural weathering of mineral deposits and from mining, mineral processing, and smelting. Along with geochemical processes and biologically mediated processes, the geologic characteristics of mineral deposits exert fundamental controls on how the deposits and their mining or mineral processing byproducts interact with the environment. Other important controls, such as climate, topographic setting, and mining and mineral processing methods, generally modify the environmental effects mandated by mineral deposit geology and geochemical processes.

Geochemical and biogeochemical controls: The ultimate driving force on the weathering of sulfide-bearing mineral deposits is the oxidation of sulfide minerals, and the resulting generation of acid. Other important geochemical controls include: (1) reaction of the acid waters with carbonate and aluminosilicate minerals; (2) precipitation of secondary minerals such as hydrous metal oxides and salts; (3) oxidation of elements such as iron, manganese, and arsenic; (4) sorption of metals onto the surfaces of particulates; (5) evaporative concentration of waters in mine workings and open pits, which can lead to precipitation of soluble efflorescent salts; (6) relative rates at which the different mineral dissolution-precipitation, oxidation, and sorption reactions occur, and; (7) the relative rates of these reactions compared to the rates of supply of oxygen and other weathering agents. Biogeochemical processes can play crucial roles in determining reaction rates at which environmental processes such as sulfide oxidation occur; for example, bacterially-catalyzed oxidation of aqueous iron greatly enhances the rate at which pyrite and other sulfide minerals weather. Bacterial sulfate reduction can also play a major role in limiting metal mobility in some reducing environments such as exist in wetlands.

Geologic controls: Mineral deposits, although complex, can readily be classified according to similarities in their geologic characteristics and mode of formation. The same geologic characteristics that distinguish different mineral deposit types also result in characteristic environmental signatures that occur naturally prior to mining and that result from mining and mineral processing. Environmentally important characteristics of a mineral deposit include: (1) amounts of pyrite and other acid-generating sulfides present in the deposit and its surrounding wallrocks; (2) amounts of acid-consuming minerals such as calcite and other carbonates in the deposit and its surrounding wallrocks; (3) relative rates at which the acid-generating and acid consuming minerals are weathered; (4) physical characteristics of the deposit (massive, vein, disseminated, permeability of host rocks, etc.), which control the access and contact time of weathering agents such as ground waters and oxygen; and (5) major- and trace element contents of the deposit and its host rocks, which help control the suites of elements dispersed into the environment.

Empirical Study of Geologic and Geochemical Controls on Mine-Drainage Composition

A continuing study of mine waters draining a number of different mineral deposit types (Plumlee et al., 1993a; Fig. 1) illustrates that environmental signatures are a readily predictable function of mineral deposit geology, geochemical processes, climate, and mining method. The mine-drainage data from diverse sites in Colorado and elsewhere are grouped in Figure 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 sulfides, coupled with smaller amounts of acid-buffering minerals present in the deposits. For example, pyrite- and enargite (Cu3AsS4)-rich ores that occur in acid-altered wallrocks (such as at Summitville, Colorado and Butte, Montana) have 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 mineralization. As a result, these ores generate highly acidic drainage waters with extreme concentrations of copper and subordinate zinc (hundreds of ppm), and other elements such as cobalt, nickel, arsenic, uranium, chromium, thorium, and rare-earth elements (hundreds of ppb to tens of ppm). In contrast, polymetallic ores that are carbonate-rich, replace carbonate-rich sediments, or occur in carbonate-rich wallrock most often generate waters with near neutral pH values; if the ores are pyrite-rich, the drainage waters can contain significant quantities of dissolved zinc (as high as 200 ppm) and lesser copper (as high as 1 ppm). For a given set of geologic characteristics, there is generally an increase in acidity and metal content from waters draining underground workings, to waters draining mine waste dumps, to open-pit waters; these progressive increases in acidity and metal content reflect increased accessibility of minerals for weathering, the increased access of oxygenated waters, and the increased evaporative concentration of the waters.

The data collected in this study also 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 et al., 1992, 1993). 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 waters, (2) the pH of the waters, and (3) the speciation and concentrations of the metals and arsenic in the drainage waters. For example, zinc is an abundant metal in most mineral deposits, is relatively mobile during the weathering of the deposits, 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

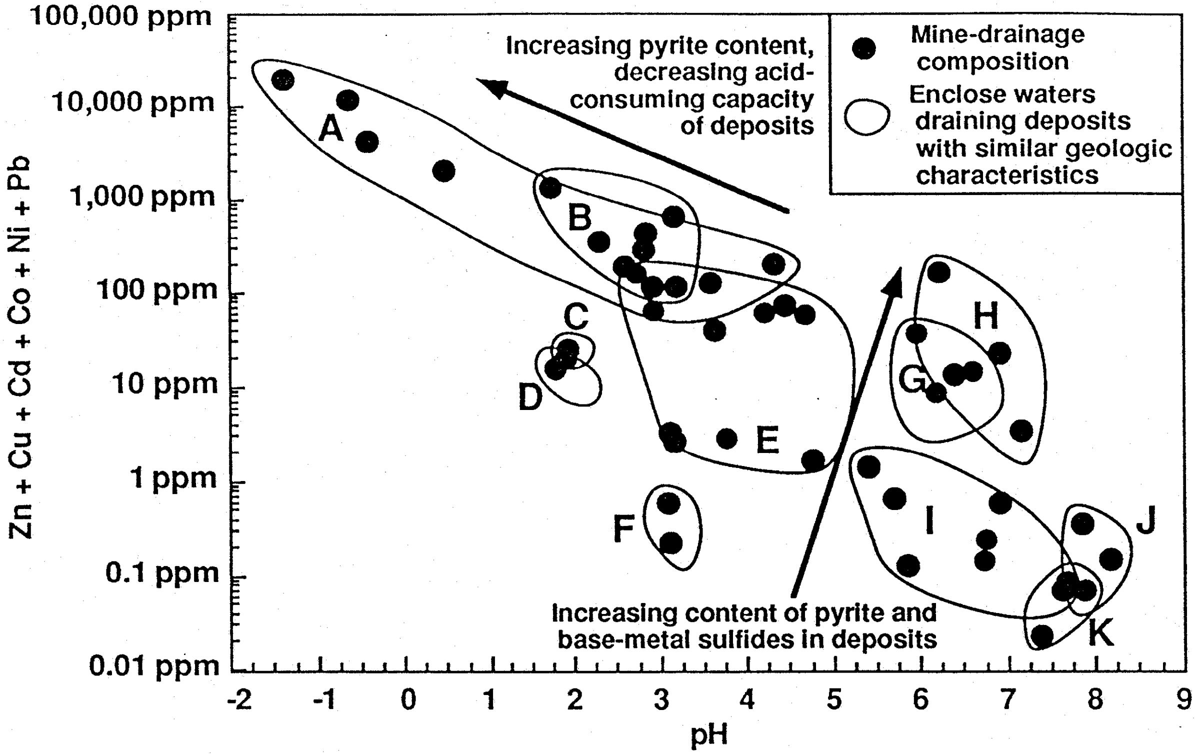

Figure 1. Ficklin Diagram plotting the pH and dissolved base metal content (given as the sum of zinc, copper, lead, cadmium, cobalt, and nickel) of mine waters draining diverse mineral deposit types. The figure is modified from Ficklin et al. (1992) and Plumlee et al. (1993a) to incorporate more recent sampling results as well additional data from Alpers and Nordstrom (1991), Davis and Ashenberg (1989), McHugh et al. (1987), Ball and Nordstrom (1989), Eychaner (1988), and Kwong (1991). The labeled fields enclose waters draining deposits with similar geologic characteristics: **A** - Pyrite-rich massive sulfides; **B** - Sulfide-rich ores (with pyrite, enargite, bornite, etc.) in wallrock highly altered to silica, alunite, kaolinite and clays; **C** - High-sulfide, low base metal hot spring ores in acid-altered wallrock; **D** - High-sulfide, low-base metal porphyry Mo ores in igneous wallrock; **E** - Pyrite- and base metal-rich polymetallic veins and disseminations in wallrock with low acid-buffering capacity; **F** - Pyrite-rich, base metal-poor veins and disseminations in wallrock with low acid-buffering capacity; **G** - Pyrite- and base metal-rich polymetallic veins that are carbonate-rich or occur in wallrock altered to contain carbonate; **H** - Pyrite- and base metal-rich, polymetallic replacements and veins in carbonate-rich sediments; **I** - Polymetallic veins with moderate to low pyrite and base metal content that are carbonate-rich or occur in carbonate-rich wallrock; **J** - Pyrite- poor polymetallic replacements in carbonate-rich sediments; **K** - Pyrite-poor, Au-Te veins and breccias with carbonate gangue.

or mostly sorbed. As a result, zinc is the dominant base metal in all of the mine-drainage waters sampled in this study with pH values greater than 5.5 (Fig. 1; Smith et al., 1992, 1993). More work is needed, however, to fully understand the role of sorption and other factors as controls on metal mobility from diverse mine sites.

Geoenvironmental models of mineral deposits

The mine drainage data discussed above, although still being updated to include additional deposit types, climate zones, etc., shows that geology- and geochemistry-based "geoenvironmental" models of mineral deposit types can be developed successfully. Prototypes of such models are currently under development at the USGS . For given deposit types, these models summarize environmentally pertinent geologic information such as: ore, gangue, wallrock, and alteration mineralogy (acid-generating vs. acid consuming, etc.); secondary mineralogy (soluble vs. non-soluble); geologic controls on permeability, ground-water flow, and oxidation; and other deposit types with similar geologic characteristics. The environmental models also provide available empirical data on environmental signatures that: (1) are present prior to mining in soils, stream sediments, and ground and surface waters of unmined deposits; (2) result from mining and mineral processing (mine drainage waters, mine wastes, mill tailings and tailings waters, and heap leach solutions), and; (3) result from smelting (smelter slag and stack emissions). For deposit types for which empirical data from existing sites are lacking, potential environmental signatures can be extrapolated from similar deposits for which data are available.

Mineral-environmental assessments of public lands

To facilitate the use of environmental geoscience information in mineral resource development and related land-use planning, the USGS is incorporating environmental risk assessments into its mineral resource assessments of public lands. A mineral resource assessment of a land unit provides a crucial geologic, geochemical, and geophysical framework upon which an environmental assessment is based. This framework includes compilation of regional geochemical and geophysical data, classifying existing mines and prospects according to deposit type, and identifying terranes favorable for the occurrence of undiscovered mineral deposit types.

The environmental assessment of a land unit has several components. First, regional geologic, geochemical, and geophysical data are used to establish baselines and to identify natural and anthropogenic sources of metal loadings into the environment. Second, likely environmental effects of mineral resources (including mined, known but unmined, and undiscovered resources) in the land unit can be estimated; this is done using geoenvironmental models of mineral deposit types discussed previously. The third component of the environmental assessment is the delineation of "litho-environmental terranes", which are rock units or groups of rock units that have a particular effect on the environment. For example, carbonate terranes generate surface and ground waters with high acid-buffering capacity, and have large capacity to mitigate the effects of acid-mine drainage. The final component is the development of an environmental risk assessment that ranks the deposit types and mining districts identified within the land unit according to the severity of their potential environmental hazards based on their geologic characteristics. For example, although a given deposit type may generate severe acid-mine drainage, occurrences of that deposit type in a carbonate-rich terrane or flow of acid waters through a carbonate terrane would lessen the potential environmental effects on the surrounding

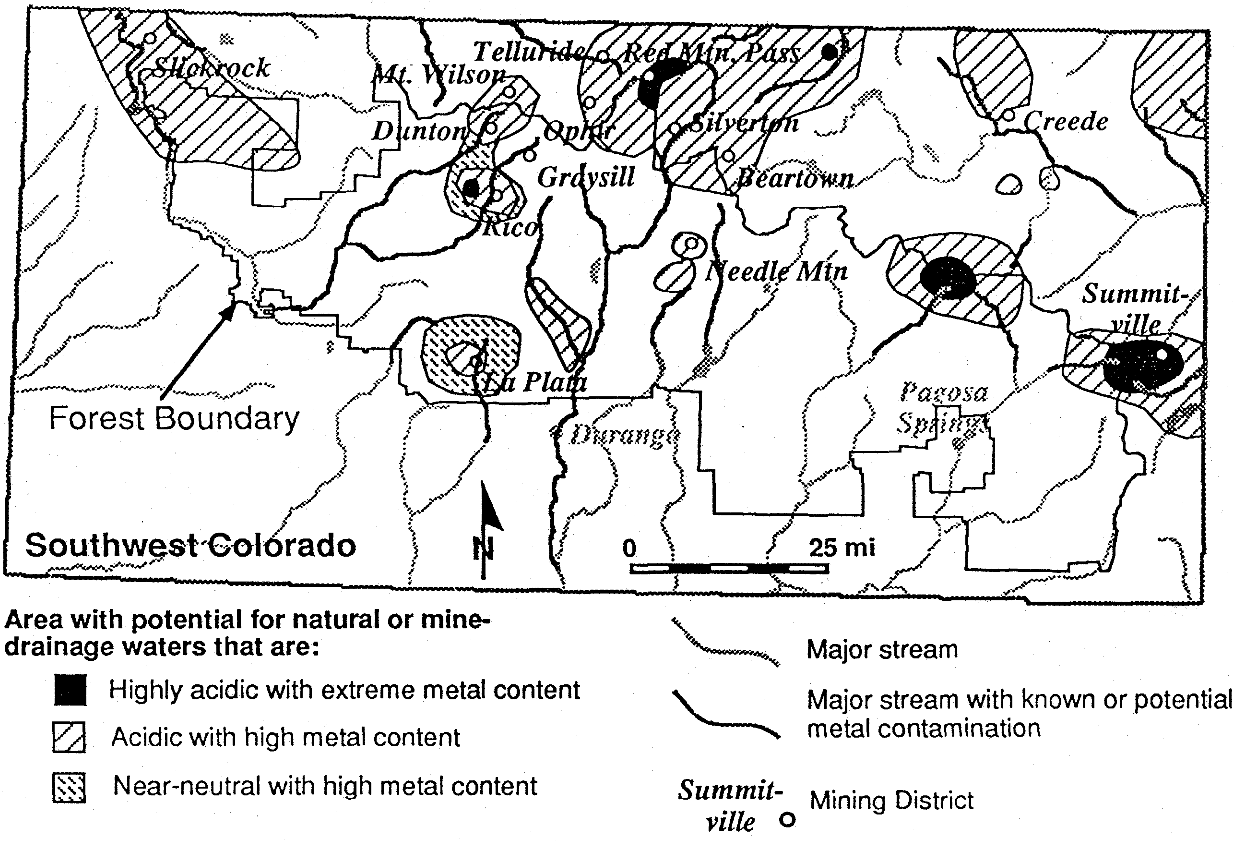

Figure 2. Geology-based natural- and mine-drainage risk assessment for the San Juan National Forest, Southwest Colorado. Modified from Plumlee et al. (1993b). Areas with potential for the generation of various natural and mine-drainage water types were defined on the basis of geologically-constrained mineral-resource tracts compiled by T. Nash, N. Foley, R. Van Loenen, A. Wallace, and S. Ludington.

land unit.

Prototype mineral-environmental assessments are currently being completed on a regional scale for Colorado, and on a more detailed scale for the San Juan National Forest in southwestern Colorado (Plumlee et al., 1993b; Fig. 2). Mineral deposit types in the San Juan National Forest vary from polymetallic carbonate replacement deposits, which tend to generate near-neutral mine drainage waters with high dissolved zinc contents, to acid sulfate Au-Cu-Ag deposits (such as Summitville), which tend to generate highly acidic waters with extreme concentrations of Cu, Zn, As, Co, Ni, U, Th, and other metals.

Potential applications

Prediction and mitigation: Following the old adage "an ounce of prevention is worth a pound of cure", the environmental models and mineral-environmental assessments can be used by industry, land managers, and regulators to help better predict and plan for potential environmental effects that would result from the development of specific mineral deposits. For example, future development of deposit types similar to those at Summitville and Butte should take into account the likely occurrence of highly acidic, metalliferous mine waters. Development of deposits of these types might therefore be more viable environmentally and economically either in arid regions or in areas with abundant nearby acid-consuming materials such as carbonate sediments.

Remediation: Geologic and geochemical information can be incorporated into remediation plans at specific mine or mineral processing sites. For example, there is increasing recognition that it is not economically viable or feasible to clean up all environmentally hazardous mine sites to pristine conditions; instead, more cleanups in the future will be carried out to baseline conditions that existed prior to mining. By defining likely baseline environmental signatures for deposit types prior to mining, geologically realistic remediation standards can be developed for post-mining cleanup. In addition, identification and characterization of other contamination sources (both natural and mining-related) within the same watershed as a mine site under remediation are needed to understand the costs and benefits of site remediation in a watershed context. As another example, detailed geologic, geochemical, and geophysical studies of mine sites are neded to fully understand the processes that are controlling metal mobility into the environment from a specific mine site; only by understanding these processes can remediaton efforts be most successful.

Identification and assessment of mine sites on public lands: Geoenvironmental models and assessments can be used to help guide the identification, assessment, and prioritization for remediation of hazardous mine sites on public lands. For example, known districts that have geologic characteristics favorable for the generation of highly acidic, metal-bearing waters should receive highest priority for site study and remediation.

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References

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 Environment Neutral Drainage), Ottawa, Canada, v. 2., p. 321-342.

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: U. S. Geol. Survey Water-Resources Investigations Report 89-4138, 46 p.

Davis, A., and Ashenberg, D., 1989, The aqueous geochemistry of the Berkeley Pit, Butte, Montana, U.S.A.: Applied Geochemistry, v. 4, p. 23-26.

Eychaner, J. H., 1988, Movement of inorganic contaminants in acidic water near Globe, Arizona, in, G. E. Mallard and S. E. Ragone, eds., U. S. Geological Survey Toxic Substances Hydrology Program--Proceedings of the Technical Meeting, Phoenix, Arizona, September 26-30, 1988: U. S. Geol. Survey Water-Resources Investigations Report 88-4220, p. 567-576.

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.

Kwong, Y. T. J., 1991, Acid generation in waste rock as exemplified by the Mount Washington minesite, British Columbia, Canada, in, Proceedings, Second International Conference on the Abatement of Acidic Drainage: MEND (Mine Environment Neutral Drainage), Ottawa, Canada, v. 1., p. 175-190.

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. Geol. Survey Open-File rept. 87-260.

Plumlee, G. S., Smith, K. S., Ficklin, W. H., Briggs, P. H., and McHugh, J. B., 1993a, 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, S. M., Toth, M. I., and Marsh, S. P., 1993b, Integrated mineral-resource and mineral-environmental assessments of public lands: applications for land management and resource planning: U. S. Geological Survey Open-File Report 93-571, 18 p.

Smith, K. S., Ficklin, W. H., Plumlee, G. S., and Meier, A. L., 1992, Metal and arsenic partitioning between water and suspended sediment at mine-drainage sites in diverse geologic settings: Proceedings, 7th International Water-Rock Interaction Conference, Park City, Utah, July 1992, p. 443-447.

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: Proceedings, 1993 Mined Land Reclamation Symposium, Billings, Montana, v. 2, p. 107-115.