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Prepared by the U. S. Geological Survey and the Colorado Geological Survey in cooperation with the U. S. Bureau of Land Management

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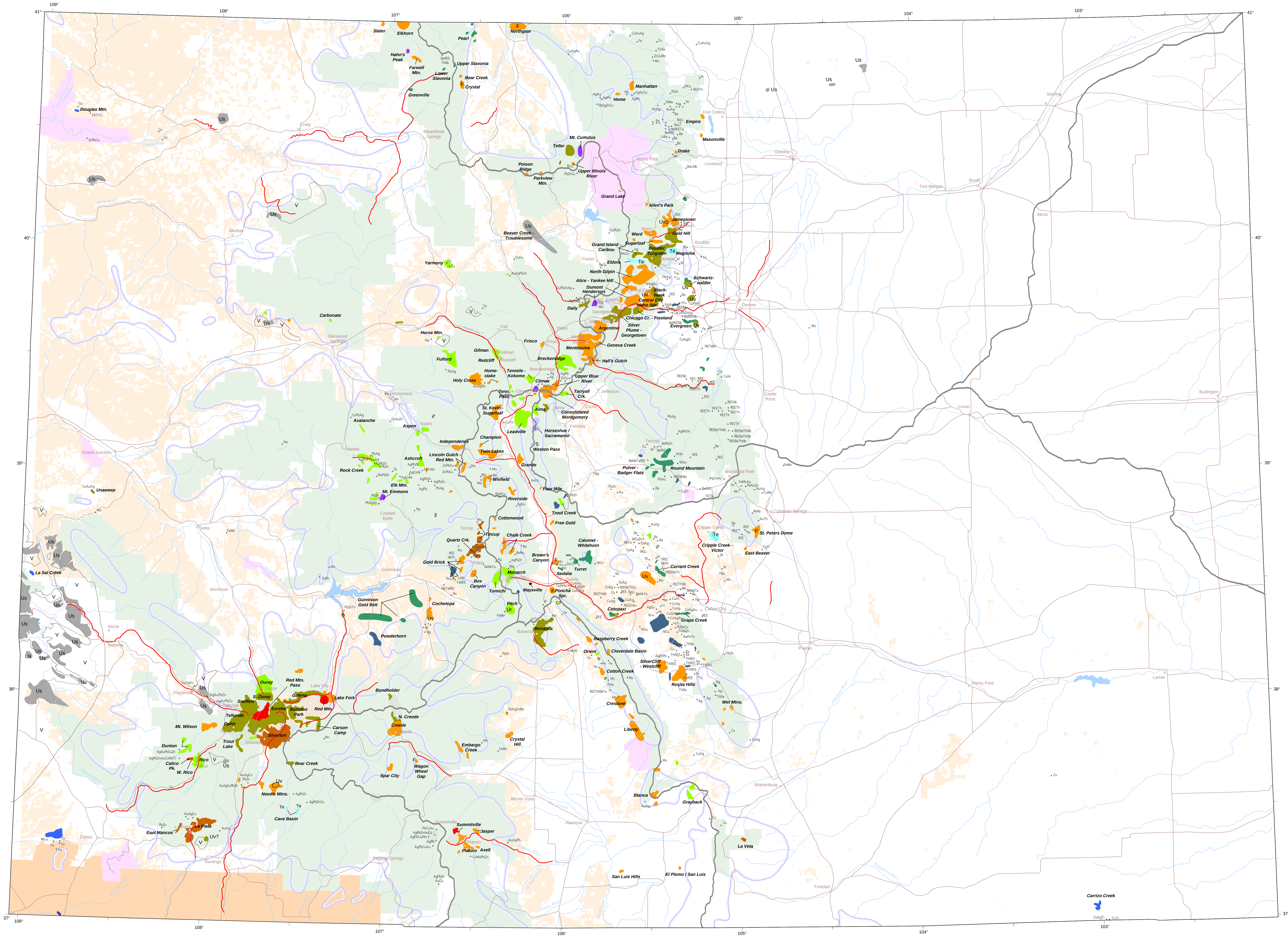

EXPLANATION

Mining district--Approximate boundaries of mining district within which most mining activity occurred; name shown where known. Predominant mineral deposit type mined and the resulting mine-drainage signatures identified by color

Potential mine-drainage signatures of mineral deposit types--A brief summary of environmentally important ore, gangue, and alteration minerals is given in parentheses. For each deposit type, estimated ranges of pH values and dissolved metal concentrations of drainage waters are listed for the different ore types or mineralogic zones; composition ranges are defined by empirical drainage data compiled for similar mineral-deposit types (Smith and others, 1995; Plumlee and others, 1994). Deposit types listed in decreasing order of likely acidity and dissolved metal content. ppm, parts per million; ppb, parts per billion; conc., dissolved concentrations; ±, may or may not be present

Deposit types likely to generate predominantly acidic, metal-rich waters

🟥 **Quartz alunite epithermal deposits**--(Pyrite-enargite-covellite-chalcopyrite veins, disseminations in wallrocks intensely altered to silica, alunite, and clays). *Waters draining most highly altered and mineralized rocks* have pH values that range from 1.5 to 3; Fe, Al, Mn conc. that range from hundreds to several thousands of ppm; Cu, Zn conc. that range from several tens to several hundreds of ppm (Cu > Zn); As, Cr, Ni, Pb, Co, U, and Th conc. that range from hundreds of ppb to several ppm

🟪 **Climax-type porphyry molybdenum deposits associated with U-rich granitic intrusions** --(Core zone with pyrite, molybdenite, fluorite, topaz; pyrite-rich intermediate zone; sphalerite, carbonates on fringes). *Waters draining pyrite-molybdenite core* have pH values that range from 1 to 3; Fe, Al conc. that range from hundreds to thousands of ppm; F conc. in hundreds of ppm; Zn, Cu conc. in tens of ppm; U conc. that range from 1 to 10 ppm. *Waters draining intermediate pyrite zone* have pH values that range from 2 to 5; Fe, Al, Mn conc. in hundreds of ppm; Zn, Cu conc. that range from <1 to 10 ppm. *Waters draining base metal-rich fringes* have pH values generally greater than 5.5; Zn, Mn conc. that range from hundreds of ppb to several tens of ppm; Fe, Cu conc. that range from hundreds of ppb to several ppm

🟧 **Polymetallic veins and disseminations in carbonate-poor rocks**--(Pyrite, chalcopyrite, sphalerite, galena, ± molybdenite). *Waters draining underground workings and mine dumps* have pH values that range from 2.5 to 5.5; Fe, Al, Mn conc. that range from tens to low hundreds of ppm; Zn conc. in tens of ppm; Cu generally in conc. that range from hundreds of ppb to several ppm (can be as high as 150 ppm in waters draining chalcopyrite-rich ores); Pb, As in several tens of ppb, although waters draining some galena rich ores can have Pb as high as 1 ppm

Uv **Uranium-rich polymetallic veins, disseminations in carbonate-poor rocks** --(Pyrite, marcasite, uraninite, sphalerite, galena, chalcopyrite). *Waters draining underground workings and mine dumps* have pH values that range from 2.5 to 5.5; Fe, Al, Mn conc. in tens of ppm; Zn, Cu conc. that range from hundreds of ppb to several tens of ppm; U conc. that range from hundreds of ppb to 5 ppm; Pb, As conc. that range from tens to several hundreds of ppb

F **Fluorine-rich veins in carbonate-poor rocks**--(Pyrite, marcasite, fluorite). *Inferred compositions of waters draining underground workings and mine dumps* have pH values that range from 2.5 to 5.0; Fe conc. in low hundreds of ppm; Al, Mn conc. in tens of ppm; Zn, Cu conc. that range from several hundreds of ppb to several ppm; F conc. that range hundreds of ppb to tens of ppm

🟫 **Polymetallic veins and disseminations in mostly carbonate-poor rock**--(Pyrite, chalcopyrite, sphalerite, galena; some calcite, rhodochrosite). *Waters draining mine dumps or waters draining underground workings in carbonate-poor rock (predominant)* have pH values that range from 2.5 to 5.5; Fe, Al, Mn conc. that range from tens to low hundreds of ppm; Zn conc. in tens of ppm; Cu conc. that range from hundreds of ppb to several ppm; Pb, As conc. in tens of ppb. *Waters draining underground workings in carbonate-rich rock (less common)* have pH values generally greater than 5.5; Zn conc. that range from 1 to 200 ppm; Fe conc. that range from several to tens of ppm; Cu conc. that range from hundreds of ppb to several ppm; Pb, As conc. that range from 1 to tens of ppb

Deposit types likely to generate both acidic and near-neutral, metal-rich waters

🟩 **Polymetallic veins and replacements in carbonate-rich sedimentary rocks and associated igneous intrusions with low carbonate content**--(Pyrite, chalcopyrite, sphalerite, galena, calcite, other carbonates). *Waters draining underground workings in carbonate-rich rock* have pH values generally greater than 5.5; Zn conc. that range from 1 to 200 ppm; Fe conc. that range from one to tens of ppm; Cu conc. that range from hundreds of ppb to several ppm; Pb, As conc. in several ppb. *Waters draining underground workings in carbonate-poor igneous intrusive rocks* have pH values that range from 2.5 to 5.0; Fe, Al, Mn conc. that range from tens to low hundreds of ppm; Zn conc. in tens of ppm; Cu conc. that generally range from hundreds of ppb to several ppm; Pb, As conc. in several tens of ppb. *Waters draining sulfide-rich mine dumps* can have pH values that range from 2.5 to 6.5; Fe, Al, Mn conc. in tens of ppm; Zn, Cu conc. that range from 1 to 100 ppm; Pb, As conc. in several tens of ppb

Ur **Uranium-rich veins and replacements in carbonate-rich sedimentary rocks**--(Pyrite, marcasite, uraninite, galena, calcite, other carbonates, ± sphalerite). *Inferred compositions of waters draining carbonate-rich rocks (predominant)* have pH values generally greater than 5.0; Fe, Zn conc. that range from 1 to tens of ppm; U conc. that range from tens to low hundreds of ppb; As conc. in tens of ppb. *Inferred compositions of waters draining mine dumps* have pH values that range from 2.5 to 6.5; Fe, Al conc. that range from tens of ppb to tens of ppm; Zn conc. that range from hundreds of ppb to one ppm; U conc. in hundreds of ppb; As conc. in tens of ppb

■ **Polymetallic veins with abundant carbonates or that occur in wallrock altered to contain carbonates**--(Pyrite, chalcopyrite, sphalerite, galena, calcite, rhodochrosite). *Waters draining many underground workings* have pH values generally greater than 5; Zn conc. that range from 1 to 200 ppm; Fe conc. that range from one to tens of ppm; Cu conc. that range from tens of ppb to one ppm; As conc. in several ppb. *Waters draining most mine dumps, tailings, carbonate-poor mine workings* have pH values that range between 2.5 and 6.5; Fe, Al, Mn conc. that range from tens to low hundreds of ppm; Zn conc. in tens of ppm; Cu conc. that range from hundreds of ppb to several ppm; Pb, As conc. that range from one to tens of ppb

Uv **Uranium-rich veins with abundant carbonates**--(Pyrite, marcasite, uraninite, galena, calcite, other carbonates, ± sphalerite). Inferred *compositions of waters draining underground workings* have pH values generally greater than 5; Fe, Zn conc. that range from 1 to tens of ppm; U conc. that range ranging from tens to low hundreds of ppb; As conc. in tens of ppb. *Inferred compositions of waters draining mine dumps* have pH values that range from 2.5 to 6.5; Fe, Al conc. that range from tens of ppb to tens of ppm; Zn conc. that range from hundreds of ppb to one ppm; U conc. in hundreds of ppb; As in tens of ppb

■ **Massive sulfide deposits**--(Lenses of massive pyrite, sphalerite, and galena, with lesser chalcopyrite). *Gunnison deposits enclosed in carbonate-bearing rocks may have waters* with pH values near 7; Zn conc. that range from several hundreds of ppb to one ppm. *Front Range and north-central deposits are mostly metamorphosed with low sulfide contents, and probably generate waters primarily* with near neutral pH values; low metal conc. *If massive sulfide lenses are present, drainage waters may* have pH values less than 4; Fe, Al conc. that range from hundreds of ppm to tens of thousands of ppm; Mn, Zn, Cu (± Co, Ni) conc. that range from tens to several thousands of ppm

Deposit types likely to generate predominantly near-neutral, metal-poor waters

Us V **Stratabound uranium-vanadium deposits in sedimentary rocks (Us--uranium-dominant, V--vanadium-dominant)**--(Pyrite, marcasite, coffinite, uraninite, uranyl vanadates, carbonates). *Inferred compositions of waters draining unoxidized ores* have: pH values generally greater than 5.5; U conc. that range from tens to low hundreds of ppb; V, Se conc. in several tens of ppb; As, Mo conc. in several ppb. *Inferred compositions of waters draining mine dumps of unoxidized ores* have pH values that are potentially acidic; Fe and Al conc. that may be as high as several ppm; U conc. that range from hundreds of ppb to several ppm; Se, As conc. in tens of ppb. *Inferred composition of waters draining oxidized vanadium-dominant ores* have near-neutral pH values; V, Se, As conc. in tens of ppb

Te **Au-Te veins and breccias**--(Gold-telluride minerals, feldspars, fluorite, carbonates, ± pyrite). *Waters draining pyrite-poor ores (predominant)* have pH values generally greater than 7; Zn conc. in several tens of ppb; U conc. that range from 1 ppb to several tens of ppb. *Inferred compositions of waters draining pyrite-rich ores (less common)* have potentially acidic pH values (2.5 to 5); Fe, Al, Zn conc. in several hundreds of ppb to tens of ppm

S **Pyrite-poor replacement ores in carbonate-rich sedimentary rocks**--(Sphalerite, galena, chalcopy-rite, lesser pyrite). *Waters draining pyrite-poor ores (predominant)* have pH values generally greater than 7; Zn, Fe conc. that range ranging from 1 to 100 ppb; As, U conc. that range from several ppb to several tens of ppb. *Waters draining pyrite-rich ores* will likely have somewhat lower pH values and higher Zn conc.

🟦 **Redbed copper deposits in carbonate-bearing sedimentary rocks**--(Chalcocite, malachite, azurite). *Inferred compositions of waters* have pH values generally greater than 6 to 7; Cu conc. that range from several tens of ppb to several ppm; Zn conc. in tens of ppb

▨ **Pegmatite or carbonatite deposits**--(Uraninite, monazite, and other rare earth minerals; no or very minor sulfides). Drainage waters are not likely to be acidic or to contain significant dissolved metals

🟨 **Insufficient geologic information at this time to infer mine-drainage signatures**

CuAgPbZn ◆ **Prospect**--Geology unknown; dominant commodities listed on map in decreasing order of abundance. Prospects with Au, Ag, Cu, Pb, Zn, Mo, Ni, and Co have highest potential for mine-drainage problems. From Streufert and Cappa (1994)

▨ **Mineralized areas, outside or adjacent to known mining district boundaries**--Predominantly unmined. Can be significant sources of natural acidic and metal-rich drainage from springs or seeps

Contour of 20 in./yr mean annual precipitation from snowfall and rainfall--Stippled pattern indicates >20 in./yr side of contour

River, stream, and (or) lake

River affected by metal contamination--Modified from Colorado Water Quality Control Division (1989)

Drainage basin boundary

Road or Highway

Durango ○ **City**

Federal land units--Approximate boundaries

National Forest Lands

BLM Lands--East of 109° latitude

National Park or National Monument

Indian Reservation

Map OF-95-26 Digital Production Note: Digital geologic and geographic data prepared with GSMAP 9.0 running under DOS 5.0 on an IBM-compatible personal computer and with MacGridzo 3.5 and Canvas 3.5 running under System 7.5 on an Apple Macintosh personal computer

Scale: 1 : 750,000
1 inch equals approximately 12 miles

10 0 10 20 30 40 50 miles

Introduction

Land management agencies are currently faced with the daunting task of identifying, assessing, and prioritizing abandoned mine sites on public lands for remediation. In Colorado, the number of abandoned mine sites on public and private lands is in excess of 20,000 (J. Herron, oral comm., 1995). Nationwide, the total number of abandoned mine sites is in excess of 500,000. Because of the large number of sites to be evaluated, procedures must be developed that can streamline and facilitate the site assessment process.

Geologic characteristics of mineral deposits are a fundamental and predictable control on the environmental effects of mining and mineral processing, and on the natural environmental conditions that exist in mineralized areas prior to mining (Plumlee and others, 1994; Smith and others, 1994; Plumlee and others, 1993; Plumlee and others, 1992; Ficklin and others, 1992; Kwong, 1993). Other important controls, such as geochemical and biogeochemical processes, climate, and mining and mineral processing methods, generally serve to modify the environmental effects dictated by geologic characteristics.

This map, compiled by the U.S. Geological Survey (USGS) in cooperation with the Colorado Geological Survey (CGS) and the U.S. Bureau of Land Management (BLM), is the first of a series of maps designed to demonstrate how geologic and geochemical information can be used on a regional scale to help assess the potential for mining-related and natural environmental problems in mining districts, unmined mineralized areas, and surrounding watersheds. A GIS (Geographic Information System) format was used to integrate geologic, geochemical, water-quality, climate, land-use, and ecological data from diverse sources. Colorado was chosen as the prototype because of the extensive geologic and geochemical data available digitally from the USGS, the State of Colorado, and other sources. Similar maps can be developed for other states or areas at a variety of scales.

The map shows potential mine-drainage hazards that may exist in Colorado metal-mining districts, as indicated by the geologic characteristics of the mineral deposits that occur in the respective districts. Likely mine-drainage signatures are defined for each mining district based on: (1) a review of the geologic characteristics of the mining district, including mineralogy, trace-element content, host-rock lithology, and wallrock alteration, and; (2) results of site specific studies on the geologic controls on mine-drainage composition (Smith and others, 1994; Plumlee and others, 1993; Ficklin and others, 1992).

Uses of the Map

This map was designed primarily for use in abandoned mine lands assessments, but can also be used for other applications such as watershed and ecosystem management, and environmental prediction and mitigation.

In abandoned mine lands assessments, land management agencies can use the map to help screen and identify mining districts with the greatest potential for acid-mine drainage, so that these districts can receive higher priority for detailed on-site characterization studies and remediation. *The map is not intended to replace on-site field studies of abandoned mine sites.* The map can be used, however, to supplement information gathered during field studies. In some on-site assessments, time and monetary constraints allow collection of only minimal water-quality data such as the pH and conductivity of mine-drainage waters. For these sites, the map can be used to place constraints on the types and concentration ranges of metals that are likely to be present in drainage waters. The map can also be used to estimate the composition of waters draining mine sites during transient storm events, waters that on-site sampling would measure only if fortuitously timed to coincide with the storm events.

Wildlife managers can use information on the map to help screen mining districts or unmined mineralized areas that have the highest potential for contributing metals of particular concern for aquatic life or wildlife health. The map also can be used to guide regional water quality studies by identifying watersheds potentially affected by natural or mining-related metal contamination.

The map can be used by both the mining industry and land management or regulatory agencies to better estimate and mitigate the potential environmental effects that may result from future mineral resource development. Combined with standard laboratory procedures used to predict acid-drainage generation (Ferguson and Morin, 1991), the geologic information can be incorporated into the earliest phases of mineral exploration to identify potential environmental problems and costs resulting from the development of specific mineral deposit types in defined geographic areas and climates. Similarly, the most beneficial mitigative procedures can be determined and instituted before mineral development occurs, thereby avoiding more costly remedial procedures after development and potential environmental problems have started.

Acknowledgments

Numerous digital data files were generated in the process of making the Colorado assessment map and many derivative digital data files were made by combining files or portions of files. The mine-drainage hazards digital data file was compiled by Geoffrey S. Plumlee, Kathleen S. Smith, and Walter H. Ficklin from the USGS. The mineral-deposit geology digital data file was compiled by Randall K. Streufert, Mark W. Davis, and James A. Cappa from the CGS and by Alan R. Wallace, Margo I. Toth, J. Thomas Nash, Geoffrey S. Plumlee, and Steven M. Smith from the USGS. Digital data compilation and graphical manipulation were done by Steven M. Smith, Gregory K. Lee, Geoffrey S. Plumlee, and Richard Tripp from the USGS and by David Taylor from the BLM. Reviewers Byron R. Berger and Arthur Bookstrom, and editors Sherman Marsh and Susan Kropschot provided many helpful suggestions that greatly improved the map's quality.

Map Preparation

Numerous digital data files exist for Colorado, including streams, cities, drainage divides, geochemical data, land use data, geology, and many more. Data files showing locations of streams, cities, drainage divides, and roads are available on CD-ROM in digital line graph (DLG) format (U.S. Geological Survey, 1990, 1993). The DLG files were downloaded and translated into files compatible with the program GSMAP for IBM-compatible computers (Selner and Taylor, 1993). Boundaries of national forests, national parks and monuments, and Indian reservations were digitized from BLM land classification maps. Additional digital files including geologic information, mining districts, and other pertinent data were digitized using GSMAP. All digital data files were then converted to ASCII coordinate files and transferred to an Apple Macintosh computer. On the Macintosh, the data files were plotted using the program MacGridzo, by Rockware, Inc. For final map preparation, the graphics files were brought as layers into the object-oriented graphics program Canvas, by Deneba software, Inc. for final map preparation. All data layers used in this compilation are currently being translated into ARC/INFO format for future use in a true GIS environment.

Mining Districts

Locations and boundaries of major mining districts as well as locations of mining prospects were compiled from several sources. Maps prepared by the CGS were used to identify the locations and boundaries of major gold-producing districts, all metal-mining districts, and smaller metal-mining prospects (Streufert and Davis, 1990; Streufert and Cappa, 1994). Locations and boundaries of uranium and vanadium districts and other areas of production were taken from Beach and others (1985). Fluorspar districts were compiled from Brady (1975). A limited number of other mining districts were added by USGS contributors.

Mineral Deposit Types

In order to identify potential mine-drainage signatures for a given mining district, it was first necessary to define the types of mineral deposits present and summarize their environmentally relevant geologic characteristics.

Geologic information for Colorado mining districts was compiled from a database (Davis and Streufert, 1990) that lists the nature of the deposit (vein versus disseminated or massive ores), important ore minerals, and host-rock lithology for each mining district. USGS personnel contributed additional information to the database on wallrock alteration mineralogy and deposit gangue mineralogy (from unpublished data sources and Vanderwilt, 1947), and then classified the deposits in each district according to similarities in their geologic characteristics such as ore and gangue mineralogy, and host rock lithology.

There was generally insufficient geologic information available to determine the deposit type for the mineral prospects shown as points on the map. As a result, only the predominant commodities for each prospect listed in Streufert and Cappa (1994) were reproduced on this map; the commodities are listed for each prospect in decreasing order of production or abundance. The commodities mined at a prospect, combined with geologic information available for nearby districts of known geology, can be used to infer some information about the geology and deposit type of individual prospects. For example, prospects with commodities such as rare earth elements (REE), thorium, and beryllium can be inferred to be pegmatite deposits with negligible sulfide minerals that would lead to acid drainage problems.

Unmined Mineralized Areas

There are a number of areas outside known Colorado mining districts that are mineralized but that have not had appreciable mining activity. These mineralized areas, such as those in the headwaters of the Alamosa River south of Summitville (Bove and others, 1995), typically contain abundant sulfide minerals such as pyrite (iron sulfide) that, when weathered, can be a significant source of natural acid drainage and metal contamination. Unmined mineralized areas that occur outside the known mining districts are identified on the map to the best of our knowledge. A number of Colorado mining districts as outlined on the map also include areas of sub-economic deposits that have not seen appreciable mining activity; in these districts, there may be some natural contributions of acid drainage in addition to mining-related drainage contributions.

Mean Annual Precipitation

Contours of mean annual precipitation amounts were digitized from a map developed by the Colorado Climate Center (1984), on the basis of data contained in Doesken and others (1984). Only areas receiving more than 20 in. of precipitation annually are shown on the map. The 20 in. mean annual precipitation contour was chosen somewhat arbitrarily, but it represents what we believe to be the approximate boundary between predominantly dry (arid) and predominantly wet (semi-arid) parts of the state.

Climate factors such as mean annual precipitation must be considered because of their effects on ground- and surface-water flow, water chemistry, and evaporation. In arid climates, ground-water tables are generally deep, and are intersected mostly by open pits; underground mine workings generally intersect the water tables only in areas of steep topography. Open pit waters or waters that do flow from springs or mines have a high likelihood of evaporating or flowing underground rather than contaminating the surface environment for long distances downstream. Due to the lack of water, chemical weathering tends to be much more limited in arid climates than in wet climates. When acid waters do form as a result of occasional storm events, they eventually evaporate and leave behind their metals and acid in the form of highly soluble salts (Plumlee, Gray, and others, 1995; Plumlee, Smith, and others, 1995). These salts can be transported by wind for significant distances and are also readily dissolved during subsequent storm events. Thus, in arid portions of Colorado outside the 20-in. mean annual precipitation contour, mining districts are at greater risk for storm-induced surface drainage from mine dumps, tailings, and windblown material rather than for perennial surface drainage from mine adits. Evaporation may lead to increased levels of acid and metals in open-pit waters; this in turn may lead to degraded ground-water quality down-gradient from open pit mines. Open-pit mining has been rather limited in Colorado, however.

In the wetter, cooler Colorado mountains (areas near or within the 20-in. precipitation contour), there is a much greater potential for perennial or long-term ephemeral surface drainage from mine workings or springs. Due to the larger volumes of water and lower rates of evaporation, metals and acid in these waters may persist well downstream from mines. There is, at the same time, a relatively high likelihood that the contaminated waters could be diluted from uncontaminated waters draining unmineralized areas. Evaporation and the formation of soluble salts remain an important process in cooler, wetter climates if rainfall or snowfall occurs sporadically. Plumlee, Gray, and others (1995) and Plumlee, Smith, and others (1995) documented the important role of soluble salts in the generation of acidic, metal-rich pulses from the Summitville mine during snowmelt or summer thunderstorms that follow extended dry periods; the mine is located at 11,500 feet elevation in an area receiving more than 50 in./yr of precipitation.

Rivers and Streams Affected By Metals

The Colorado Water Quality Control Division (WQCD) periodically reviews Colorado rivers and streams for impact from a variety of contaminants such as metals, fertilizers, and bacteria, and prepares maps showing the results of the reviews. The layer on this map showing streams and rivers affected by metals was modified from a map prepared by the WQCD (1989). Affected reaches of streams and rivers were identified by WQCD as those for which aquatic life and (or) agricultural use standards were exceeded for one or more of various metals such as copper, zinc, and cadmium.

Although most of Colorado’s metal-affected streams are clearly related to metal-mining activities, it should be noted that there are some streams, such as the Platte River north of Denver that are likely affected, at least in part, by urban activities. There are also some rivers, such as the Yampa River and some of its tributaries west of Steamboat Springs, that are affected by metals released by coal mining activities.

Mine-drainage Models of Mineral Deposits and Likely Mine Drainage Signatures of Mining Districts

A compilation of mine-drainage compositions from diverse mineral deposit types shows that mine waters draining mineral deposits with similar geologic characteristics have metal concentrations and pH values that cluster within distinctive ranges (Smith and others, 1994; Plumlee and others, 1993; Plumlee and others, 1992; Ficklin and others, 1992). In addition, the elemental suites of metals present in mine-drainage waters typically reflect the same characteristic suites of metals contained in the mineral deposits. For example, deposits containing pyrite (an iron sulfide), enargite (a copper-arsenic sulfide), and other copper sulfides in highly altered host rocks at Summitville, Colorado predominantly generate highly acidic waters with thousands of parts per million (ppm) dissolved iron and aluminum, hundreds of ppm dissolved copper and zinc, and several to tens of ppm dissolved cadmium, cobalt, arsenic, nickel, and uranium; these water compositions result from the lack of acid-buffering capacity in the highly altered wallrocks, coupled with the sulfide-rich nature of the ores. In addition, the copper-rich nature of the ores at Summitville is reflected by similar enrichments of copper over zinc in the mine-drainage waters compared to those draining most other mineral deposit types. In contrast, deposits of pyrite, sphalerite (a zinc sulfide), and galena (a lead sulfide) that occur in carbonate-rich host rocks at Leadville, Colorado tend to generate drainage waters that can contain high levels of dissolved zinc, but are generally of near neutral pH. Mine-drainage waters may also be affected by the mining technique used to extract the ore. Generally, waters from open-pit mines and water draining mine dumps tend to have somewhat more acidic, metal-rich compositions than waters draining underground workings; this is related to the increased surface areas exposed to weathering in open-pit mines and mine dumps, increased accessibility of oxygenated waters, and increased opportunities for evaporative concentration (Plumlee and others, 1993).

These empirical studies show that, given a good knowledge of mineral-deposit geology in a given district, it is possible to estimate or predict likely ranges of pH and metals present in waters draining mine workings and mine wastes in any given district (Smith and others, 1994; Plumlee and others, 1993).

On the Colorado map, metal-mining districts have been grouped according to their geologic characteristics and their resulting potential for mine-drainage hazards. The deposit types are listed in the map explanation in decreasing order of acidity and metal content (that is, increasing water quality) of their potential mine-drainage compositions. The mine-drainage signatures listed are those that we believe are most likely to occur based on the empirical data available to date and our best knowledge of the geology of each district. Because mineral-deposit geology is highly complex, with significant spatial variations in ore mineralogy, host rock lithology, and host rock alteration possible in the same mining district, the explanation shows a range in mine drainage compositions that might occur in different mineralogic zones, wallrock alteration zones, or host rocks for various deposit types within a given mining district.

Empirical data on mine drainage compositions have not been collected for all deposit types and all geologic characteristics. In districts containing deposit types for which empirical data are lacking, some limits on drainage compositions can be inferred by analogy with deposit types of similar geology.

References

Beach, R.A., Gray, A.W., Peterson, E.K., and Roberts, C.A., 1985, Availability of Federal land for mineral exploration and development in western states--Colorado, 1984: U.S. Bureau of Mines Special Publication, 40 p., 2 pl.

Bove, D.J., Barry, T., Kurtz, J., Hon, K., Wilson, A.B., VanLoenen, R.E., and Kirkham, R. M., 1995, Geology of hydrothermally altered areas within the upper Alamosa River basin, Colorado, and probable effects on water quality, *in*, Posey, H.H., Pendleton, J.A., and Van Zyl, D., eds, Summitville Forum Proceedings; Colorado Geological Survey Special Publication 38, p. 35-41.

Brady, B.T., 1975, Map showing fluorspar deposits in Colorado: U.S. Geological Survey Mineral Investigations Resource Map MR-70, scale 1:500,000.

Colorado Climate Center, 1984, Colorado Average Annual Precipitation Map, 1951-1980.

Colorado Water Quality Control Division, 1989, Colorado nonpoint assessment report, 1989 addendum:189 p.

Davis, M.W., and Streufert, R.K., 1990, Gold occurrences of Colorado: Colo. Geol. Survey Resource Series 28, 101 p.

Doesken, N.J., McKee, T.B., Richter, B.D., 1984, Analysis of Colorado average annual precipitation for the 1951-1980 period: Fort Collins, Colorado State Univ., Climatology Report 84-4, 53 p.

Ferguson, K.D. and Morin, K.A., 1991, The prediction of acid rock drainage--lessons from the database: Proc., 2nd Intl. Conference on the Abatement of Acidic Drainage, MEND Program, v. 3, p. 83-106.

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: Proc., 7th Intl. Water-Rock Interaction Conference, Park City, Utah, July, 1992, p. 381-384.

Kwong, Y.T. J., 1993, Prediction and prevention of acid rock drainage from a geological and mineralogical perspective: Ontario, Canada, MEND Program, Project 1.32.1, CANMET, 47 p.

Plumlee, G.S., Gray, J.E., Roeber, M.M., Jr., Coolbaugh, M., Flohr, M., and Whitney, G., 1995, 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, Colo. Geol. Survey Special Publication 38, p. 13-22.

Plumlee, G.S., Smith, K.S., and Ficklin, W.H., 1994, Geo-environmental models of mineral deposits, and geology-based mineral-environmental assessments of public lands: U. S. Geological Survey Open-File Report 94-203, 7 p.

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: Proc., 7th Intl. Water-Rock Interaction Conference, Park City, Utah, July 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: Proc., 1993 Mined Land Reclamation Symposium, Billings, Montana, v. 1, p. 176-186.

Plumlee, G.S., Smith, K.S., Mosier, E.L., Ficklin, W.H., Montour, M., Briggs, P.H., and Meier, A.L., 1995, Geochemical processes controlling acid-drainage generation and cyanide degradation at Summitville, *in* Posey, H. H., Pendleton, J.A., and Van Zyl, D., eds: Proc., Summitville Forum ‘95, Colo. Geol. Survey Special Pub. 38, p. 23-34.

Selner, G.I., and Taylor, R.B., 1993, System 9, GSMAP, and other programs for the IBM PC and compatible microcomputers, to assist workers in the earth sciences: U.S. Geological Survey Open-File Report 93-511, 363 p.

Smith, K.S., Plumlee, G.S., and Ficklin, W.H., 1994, Predicting water contamination from metal mines and mining waste: Notes, Workshop No. 2, Intl. Land Reclamation and Mine Drainage Conference and Third Intl. Conference on the Abatement of Acidic Drainage: U.S. Geological Survey Open-File Report 94-264, 112 p.

Streufert, R.K., and Cappa, J.A., 1994, Location map and descriptions of metal occurrences in Colorado with notes on economic potential: Colorado Geological Survey Map Series 28, 35 p., 1 pl.

Streufert, R.K., and Davis, M.W., 1990, Gold districts and placers of Colorado, plate 1 of 2 in Davis and Streufert, Gold occurrences of Colorado: Colo. Geol. Survey Resource Series 28, 101 p.

U.S. Geological Survey, 1990, 1:2,000,000-scale Digital Line Graph (DLG) data: U.S. Geological Survey, Digital Data Series DDS-4, CD-ROM.

U.S. Geological Survey, 1993, 1:100,000-scale Digital Line Graph (DLG) data, hydrography and transportation: U.S. Geological Survey, U.S. GeoData, Area 9—Central Plains States, CD-ROM.

Vanderwilt, J.W., 1947, Mineral resources of Colorado: Denver, Mineral Resources Board, 547 p.

MAP SHOWING POTENTIAL METAL-MINE DRAINAGE HAZARDS IN COLORADO, BASED ON MINERAL-DEPOSIT GEOLOGY

by

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