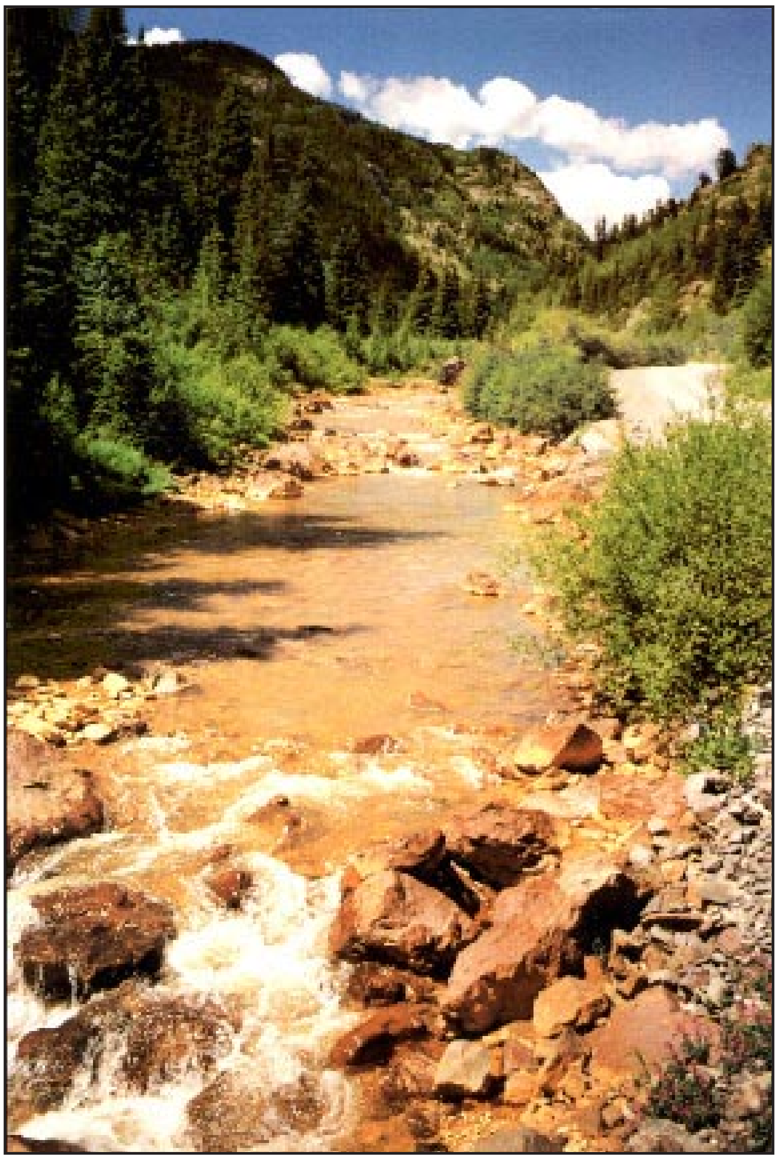

Environmental Considerations of Active and Abandoned Mine Lands

Lessons from Summitville, Colorado

U.S. GEOLOGICAL SURVEY BULLETIN 2220

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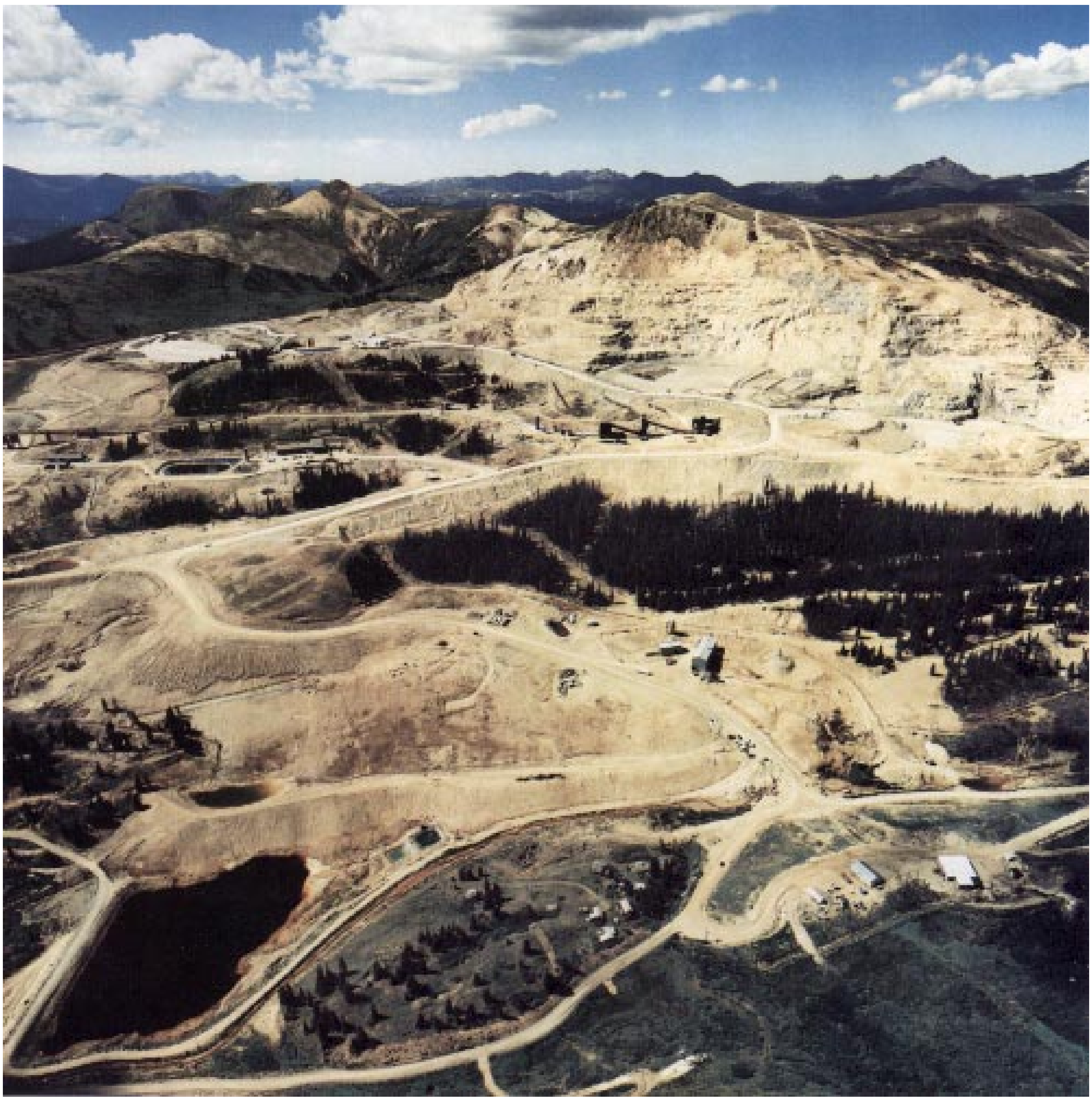


Environmental Considerations of Active and Abandoned Mine Lands

Lessons from Summitville, Colorado

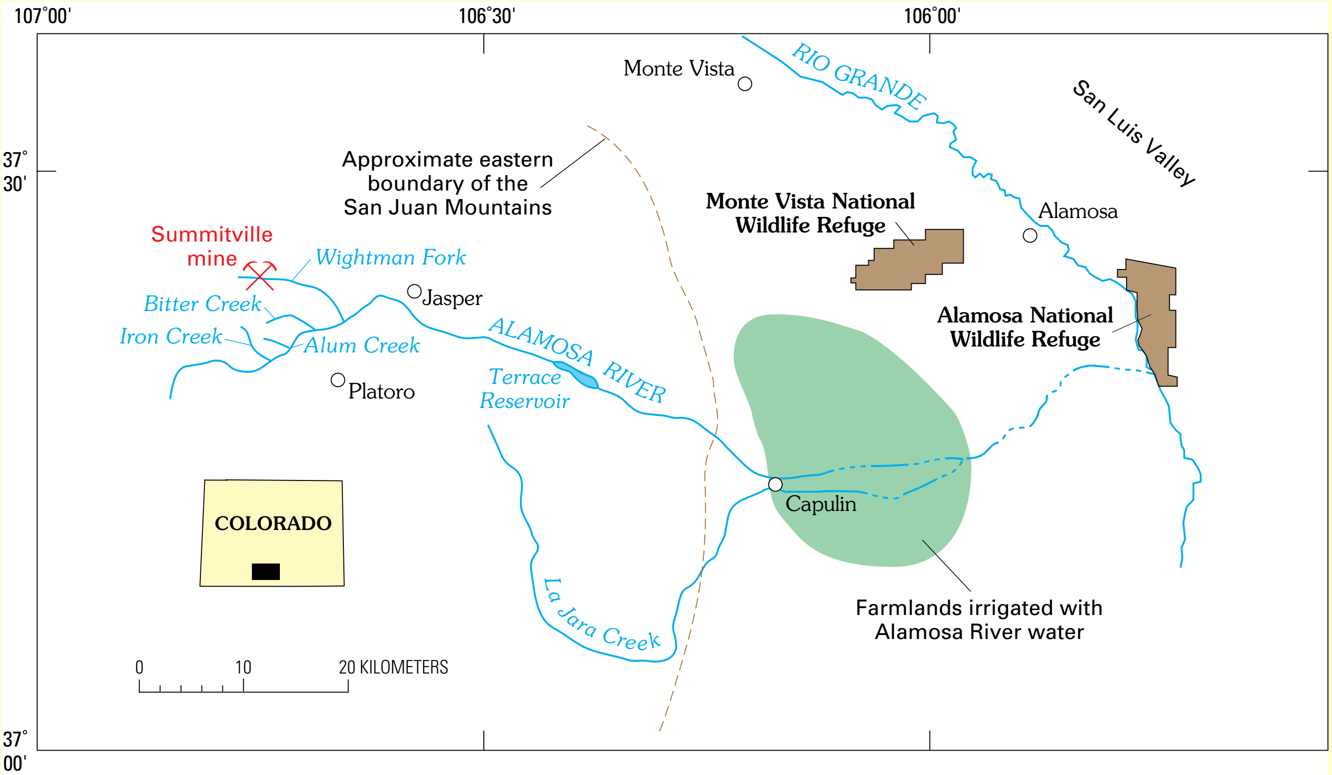
Metals and minerals are essential components of a highly industrial society. In the United States part of this demand has been met through domestic mining of metals and minerals in almost every State of the Nation. Historically, when mines were no longer economic, individual mines or whole mining districts were abandoned with little or no consideration for future environmental impacts. Current awareness has made the public more concerned about the effects of mining. The deleterious effect of historic mining activity is a national problem. There are between 100,000 and 500,000 abandoned or inactive mine sites in the United States; a total of 26 States, predominantly in the West, have more than 50 U.S. Environmental Protection Agency (EPA) Superfund restoration sites related to non-fuel mining activity. The Summitville mine site in Colorado is an example of what can go wrong.

From 1985 through 1992, the Summitville open-pit mine produced gold from low-grade ore using cyanide heap-leach techniques, a method to extract gold whereby the ore pile is sprayed with water containing cyanide, which dissolves the minute gold grains. Environmental problems at Summitville include significant increases in acidic and metal-rich drainage from the site, leakage of cyanide-bearing solutions from the heap-leach pad into an underdrain system (designed to catch solutions containing gold and cyanide that leaked through the liner under the heap), and several surface leaks of cyanide-bearing solutions into the Wightman Fork of the Alamosa River. The mine's operator had ceased active mining and had begun environmental remediation, including treatment of the heap-leach pile and installation of a water-treatment facility, when it declared bankruptcy in December 1992 and abandoned the mine site. The EPA immediately took over the Summitville site under EPA Superfund Emergency Response authority. Summitville was added to the EPA National Priorities List in late May 1994. The total cost of the cleanup has been estimated at $100 to $120 million. EPA's remediation efforts include treatment of cyanide solutions remaining in the heap-leach pad, detoxification of the heap, plugging of the Reynolds adit (a major source of acid- and metal-rich drainage from the site), backfilling of the open pit with acid- and metal-generating waste dump material, and capping of the backfilled pit to prevent water inflow.

Summitville has focused nationwide attention on the environmental effects of modern mineral-resource development. Soon after the mine was abandoned, Federal, State, and local agencies, along with Alamosa River water users and

Superfund

The Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), commonly called Superfund, was passed into law in December 1980. It established a program to identify sites from which releases of hazardous substances into the environment have or might occur, to provide for cleanup by responsible parties or the government, to evaluate natural resource damage, and to create procedures for cost recovery related to cleanup activities.



Summitville mine area in the San Luis Valley of Colorado.

private companies, began extensive studies at the mine site and surrounding areas. These studies included analysis of water, soil, livestock and vegetation. The role of the U.S. Geological Survey (USGS) was to provide geologic and hydrologic information about the mine and surrounding area and to describe and evaluate the environmental condition of the Summitville mine and the downstream effects of the mine on the San Luis Valley. The environmental condition of the Summitville area is both a result of the geologic evolution of this area that culminated in the formation of precious-metal mineral deposits and a result of the mining activity. Understanding the geologic and hydrologic history of this area is a critical part of understanding the environmental puzzle at Summitville.

ACID MINE DRAINAGE

Mining activity occurs in areas that have high concentrations of economically important materials, such as gold, silver, copper, cobalt, iron, lead, and zinc. These areas may also contain high concentrations of noneconomic elements such as arsenic, selenium, mercury, and sulfur, whose presence is closely tied to the formation of the heavy metals. Many of these economic and noneconomic elements can be hazardous if released into the environment. Even without mining, mineralized areas can naturally adversely affect the environment.

A common process that results in dispersion of elements from a mineralized site is acid drainage. When acid drainage results from mining activity, it is more specifically called acid mine drainage. As the name implies, acid mine drainage is the formation and movement of highly acidic water rich in heavy metals. This acidic water forms principally through chemical reaction of surface water (rainwater, snowmelt, pond water) and shallow subsurface water with rocks that contain sulfur-bearing minerals (mainly pyrite), resulting in sulfuric acid. Heavy metals can be leached from rocks that come in contact with the acid, a process that may be substantially enhanced by bacterial action. The resulting fluids may be highly toxic and when mixed with groundwater, surface water, and soil may have harmful effects on humans, animals and plants.

Mining accentuates and accelerates natural processes. The development of underground workings, open pits, ore piles, mill tailings, and spoil heaps and the extractive processing of ores enhance the likelihood of releasing chemical elements to the surrounding area in large amounts and at increased rates relative to unmined areas. Studies describing both the extent and effect of acid drainage both in unmined mineralized areas and in areas containing inactive and abandoned mines are required if the environmental impact of heavy metals is to be understood. Studies in unmined mineralized areas describe the natural, baseline chemical characteristics and variations of the mineralized areas. By

pH

All natural waters contain free hydronium (H_3O^+) and hydroxyl (OH^-) ions. Acidity is measured by the concentration of hydrogen ions, called pH, which is the negative logarithm of the hydrogen ion activity. Neutral solutions have pH values of 7. If the pH is greater than 7 the water is basic, and if the pH is less than 7 the water is acid. Acids have a sour taste. For example, vinegar (a strong acid) has a pH of about 4.6, whereas the pH of rainwater is about 6 (a weak acid). The pH of acid mine drainage may be less than 2 but commonly is between 2 and 5.

Elements in Solution

Sulfuric acid in liquid form breaks down into hydronium ions (H_3O^+) and sulfate ions (SO_4^{2-}) and can carry many metals in solution, as both simple and complex ions. For example, copper can be transported in solution as simple copper ions (Cu^{2+}) and deposited as copper sulfate ($CuSO_4$); iron can be transported as ferrous or ferric ions (Fe^{2+} or Fe^{3+}) and deposited as ferric hydroxide ($Fe(OH)_3$). The variety of simple and complex ions in solution depends in part on the pH of the solution, the amount of oxygen dissolved in the solution, and the concentrations of the cations (positively charged ions) and anions (negatively charged ions) in the solution.

LESSONS FROM SUMMITVILLE

ACTIVE VOLCANOES ONCE COVERED SOUTHWESTERN COLORADO

The Summitville gold mine is in the San Juan Mountains of Colorado in an area that was once covered with steep-sided volcanoes. These volcanoes formed about 30 million years ago but have been partly destroyed by natural erosion, leaving behind remnants of volcanic debris. Summitville is part of a volcano whose summit collapsed, forming a caldera. After the caldera formed, lava eruptions continued at the surface and intrusions formed beneath the surface. At the same time, rocks inside the volcano were exposed to hot, corrosive water produced by the volcanic system, a process called hydrothermal alteration.

The region around the Summitville mine is covered with creeks of small and intermediate size that drain into the Alamosa River and form the upper Alamosa River basin. The downward-cutting action of these creeks has exposed the hydrothermally altered rocks and allowed geologists to examine these rocks in detail. Two main episodes of hydrothermal alteration occurred in the upper Alamosa River basin. The older period of alteration affected about 11 square kilometers of rock in the Iron, Alum, and Bitter Creek basins and a roughly equivalent area at Jasper. A younger period of alteration, corresponding to renewed hydrothermal activity almost 8 million years later, affected about 3 square kilometers surrounding the Summitville mine area and led to the formation of precious-metal mineral deposits.

The Summitville mine, Iron, Alum, and Bitter Creek basins, and Jasper area are all located on a zone of weakness in the Earth's crust. During the past 65 million years, this zone was the focus of many cycles of magma intrusion, hydrothermal alteration, and mineral formation. The magma intrusions in the Iron, Alum, and Bitter Creek basins and in the Jasper area have been exposed by erosion, and geologists have shown that the origins of the intrusions and the rock alteration are closely connected. At Summitville, however, the intrusive body is not exposed at the surface because it is covered by almost 600 meters of younger lava. By using the geologic situation of the Iron, Alum, and Bitter Creek basins and the Jasper area as an analogy, geologists assume that the buried intrusion at Summitville is also closely tied to the rock alteration and mineral deposits observed at the surface.

One of the strong similarities between the Summitville mining district and the Iron, Alum, and Bitter Creek basins is the presence of altered rocks that have been extremely corroded by sulfuric acid during hydrothermal alteration. This type of rock disintegration is known as acid-sulfate alteration. The hot fluids in the Iron, Alum, and Bitter Creek basins did not carry silver or gold in solution and thus did not produce an economic mineral deposit. In contrast, the fluids at Summitville carried gold, silver, and copper. When these elements were deposited from the fluids, a precious-metal and base-metal mineral deposit formed. The contrast between the Iron, Alum, and Bitter Creek basins and Jasper area and the Summitville mining area is very important. The former areas, as shown in the photograph, are undisturbed by mining or extensive exploration and can be used to characterize and compare background sites adjacent to the Summitville mining area.

Formation of Volcanoes

Heating in the Earth's interior results in melting of previously formed rocks to produce magma. Magma is less heavy than the surrounding rocks and moves upward, pushing aside surrounding colder rocks or moving through regions of pre-existing weakness. If magma reaches the surface, it spills out and flows across the land as lava flows or congeals near the eruption site as a dome; if magma below the surface is under enormous pressure, it can be violently blown into the atmosphere as volcanic ash. Continued eruption in one area eventually builds a volcano fed from underground stores of magma. Sudden eruption or sideways movement of underground magma can produce a subsurface void causing the volcano summit to collapse around a roughly circular depression called a caldera. Some calderas are tens of kilometers in diameter. During the building of such a volcano, the magma can cool and solidify before reaching the surface to form dikes (near-vertical, narrow sheets), sills (near-horizontal, narrow sheets), or irregular shaped masses beneath the volcano. As the magma cools it discharges fluids (primarily water containing various dissolved metals and salts) and gases and also heats local groundwater, which begins to move through the volcano. These fluids and gases can be very corrosive and attack the surrounding rocks, producing areas of hydrothermal alteration. Cooling of the fluids and gases can precipitate new minerals, including gold, silver, and sulfides, in sufficient amounts to form a mineral deposit.

combining these baseline studies with information from areas containing inactive and abandoned mines, it is possible to provide:

- An assessment of the intensity and extent of environmental impact due to acid mine drainage
- An understanding of natural processes to detect and predict where and when acid mine drainage might occur

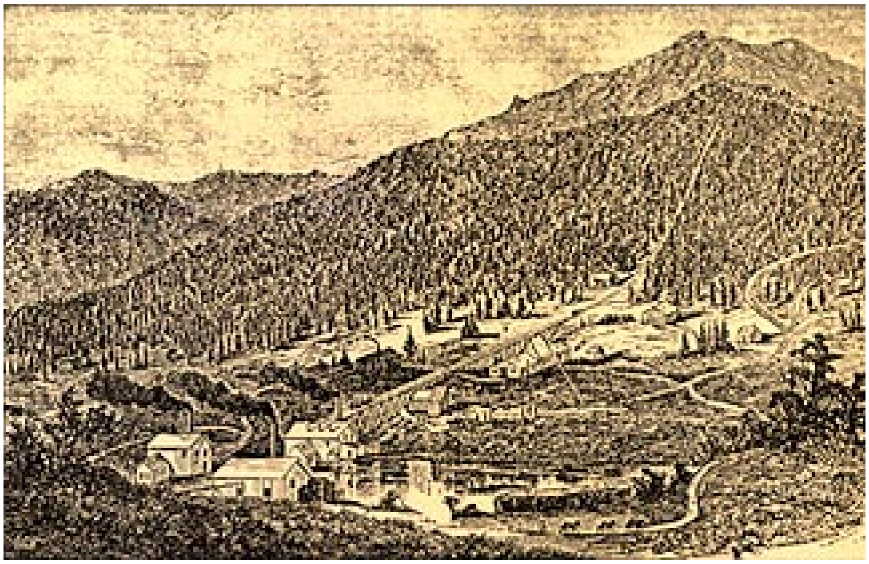
The production and consequences of acid drainage involve the movement of various chemical elements through the environment as a result of physical, chemical, and biological processes. Collectively, these processes form the biogeochemical cycle.

Geology (the physical, structural, and historical relations between rocks), geochemistry (the chemistry of rocks and their constituents), geophysics (the physics of rocks and their constituents), biochemistry (the chemistry of biological substances), and hydrology (the properties, distribution, and effects of water at the Earth's surface and in the subsurface) are the major scientific disciplines used to investigate the biogeochemical cycle and, consequently, are used in a multidisciplinary fashion to study acid mine drainage.

USGS studies at the Summitville mine in Colorado and adjacent parts of the San Luis Valley used this integrated approach. Many of the environmental problems associated with Summitville are the result of acid mine drainage, and in this document we describe studies that allow acid drainage to be understood in more detail. USGS activities at Summitville were undertaken in part to provide other Federal and State agencies with data and interpretations and to develop prototypes for future studies involving inactive and abandoned mines.

The Biogeochemical Cycle

Three principal ingredients make up the biogeochemical cycle. (1) Source of chemical elements (where do they come from?). The source determines how elements are physically and chemically distributed and to what extent they are available within the cycle. (2) Transport mechanisms (how do elements move through the environment?). Commonly, these mechanisms include water, wind, gravity, and living organisms and are heavily influenced by climate. (3) Sites (fate) of deposition (where and why does transport stop?). For example, the elements may be deposited as a part of the sediment in a reservoir or they may be taken up by a plant and perhaps become part of the food chain. Not all deposition sites are permanent, and chemical elements can be remobilized if physical or chemical conditions change.



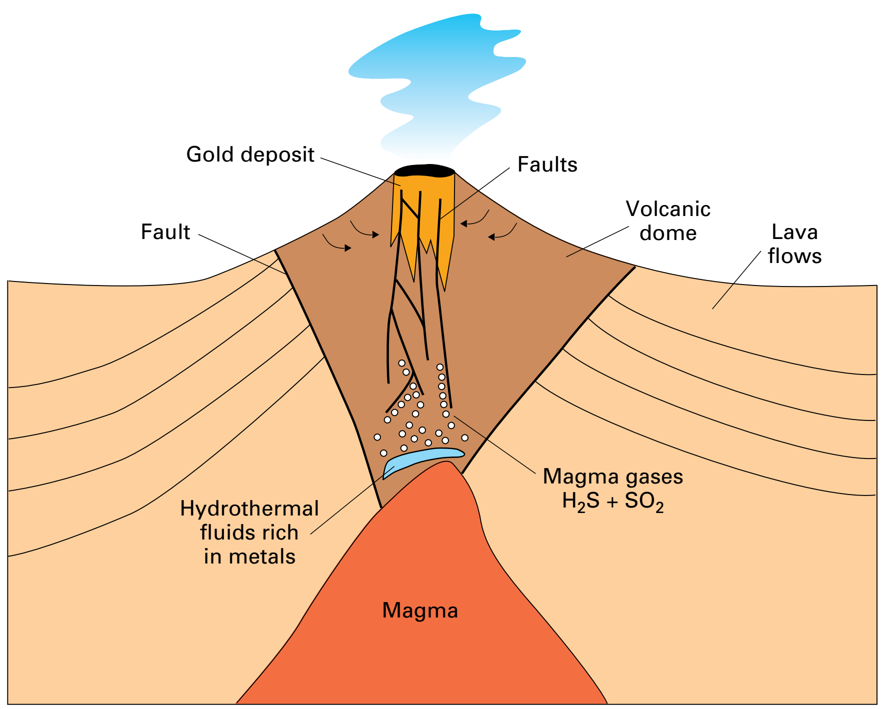
Background Sites

An assessment of the environmental impacts of mining at Summitville (or any mining facility) should be related to areas that are undisturbed. Scientists ask, "How does the environment of a mined area compare to what we might reasonably expect in the area if there had been no human interference?" Ideally, information about an area prior to human interference would serve this purpose; however, this type of information is rarely available. In most cases, comparison areas are chosen that are geologically similar but have not experienced human interference. The effect of human interference is commonly evaluated by simple statistical techniques using the comparison, or background, site to provide a baseline.

GOLD IN AN ANCIENT VOLCANO

Gold mining at Summitville and the minerals that produce acid mine drainage are closely related to each other. How did such a close relation develop? One way to answer this question is to study modern volcanoes that appear to be similar to ancient volcanoes in the Summitville region. For example, the unaltered rocks in the Summitville region are very similar to rocks at Mount St. Helens in Washington. The violent eruption of Mount St. Helens in 1980 was accompanied by the growth of a volcanic dome within the summit crater. This dome represented the surface eruption of very viscous (thick and sticky) magma that had slowly risen through the bowels of the volcano. During and after the growth of the bulbous dome at Mount St. Helens, large volumes of acidic gas and water vapor poured from the volcano summit as a result of magma cooling within the volcano.

Based on drilling information, it is known that a similar dome lies beneath the Summitville mine site, and, by analogy to Mount St. Helens, we can describe the geologic evolution at Summitville in the following way. Molten magma beneath Summitville contained many dissolved gases, mainly sulfur dioxide (SO_2) and hydrogen sulfide (H_2S), water, and metals. As the magma cooled, the gases and water separated, each taking many metals with them. The gases, being very light, ascended quickly along faults and fractures that cut through the volcano. During their rise, the magmatic gases and water vapor combined to form sulfuric acid (H_2SO_4), which is highly corrosive. The sulfuric acid dissolved minerals in the surrounding rocks, making the rock porous, a process called acid leaching. The metal-bearing waters, being heavier than the gases, moved upward at a slower pace but still along

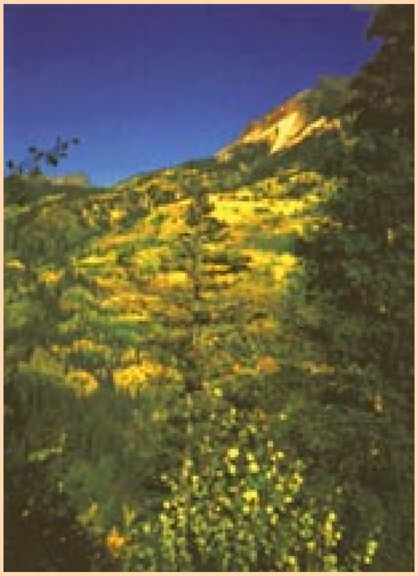


Cross section of a volcano. Magma is below the volcanic dome, and magma gases are separating from the liquid magma.

the same complex of faults and fractures. Normally rocks are able to withstand severe attack by acid solutions because they quickly neutralize the waters, a process called acid buffering. The quantity of acidic gases and waters that attacked the rocks at Summitville must have been great because the intensity of acid alteration is extreme. These altered rocks no longer have a natural acid-buffering capacity and can no longer neutralize the fluids. The ascending gases caused the rock porosity (the volume of open space in a rock relative to its total volume) and permeability (the ability of a rock to transmit fluid) to increase (by acid leaching) and hence eased the upward movement of the later fluids.

The most important metals in the fluids were gold, silver, copper, iron, lead, and arsenic, but the fluids also contained abundant sulfur and salt. The volcano probably had a well-developed groundwater table, and mixing of rising hot, magmatic fluids and cooler groundwater was inevitable. Because of the vastly different temperatures and chemical compositions of these mixtures and fluids, many metals and compounds were deposited from the solutions as solid minerals in fractures and pore spaces. This account fits well with the common observation of gold and iron pyrite, as well as copper- and arsenic-bearing sulfur minerals such as covellite (a copper ore mineral) and enargite (a copper ore mineral containing arsenic), in the altered rocks at Summitville.

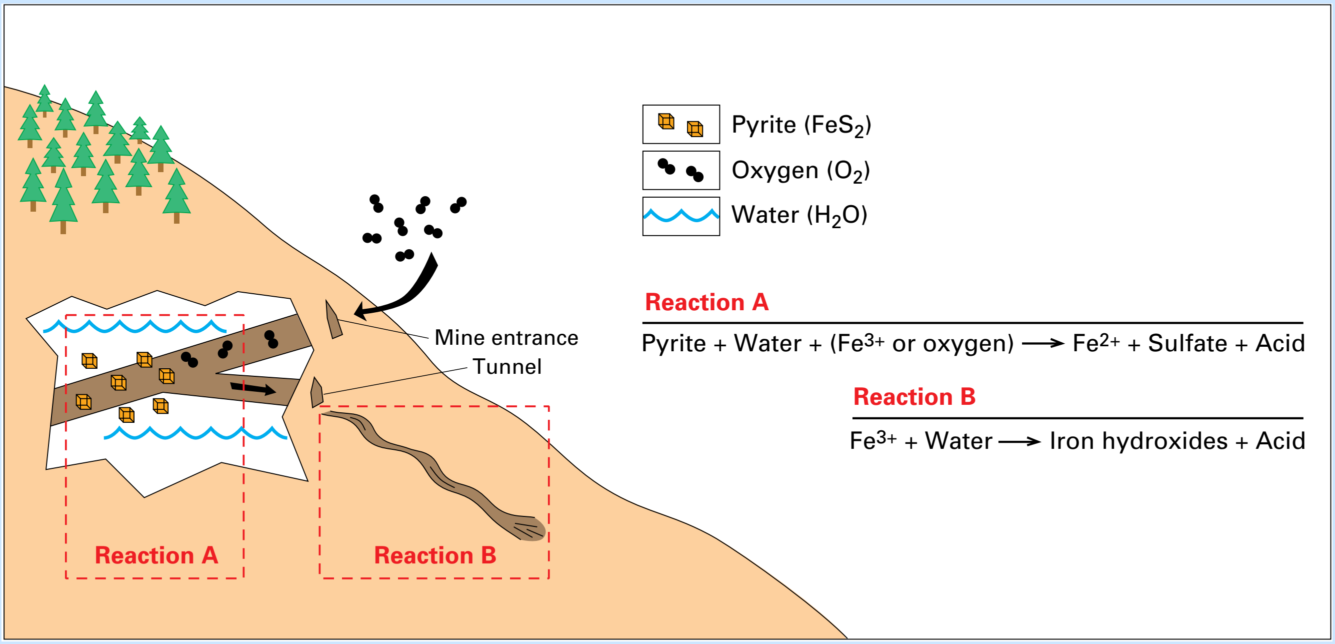
As a result of these complicated chemical processes, rocks that originally contained no gold were converted to highly altered ore rocks containing large amounts of gold. It is this gold ore that has been sought and mined at Summitville since gold was first discovered there in 1870. Equally important from an environmental standpoint, however, was the formation of metal sulfides, particularly pyrite (FeS_2), which are essential to the generation of acid drainage.



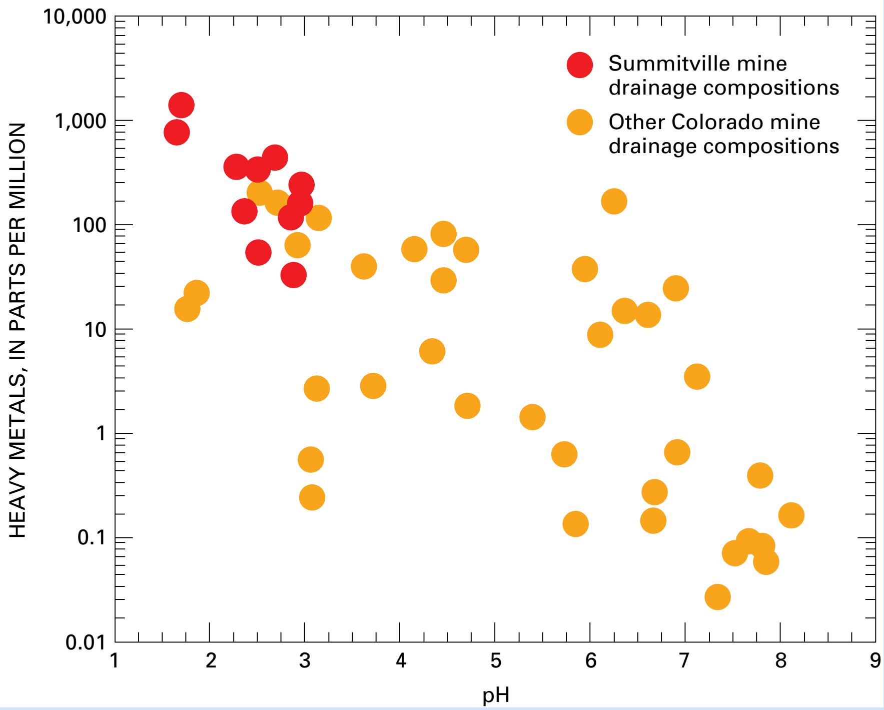
MINING OF GOLD AND FORMATION OF ACID MINE DRAINAGE AT SUMMITVILLE

Before 1960, miners at Summitville dug many underground tunnels to remove the high-grade gold ore concentrated along fractures and faults; however, much of the gold was scattered in small amounts and in minute grains over large areas of altered rock. Modern gold extraction technology made it possible to mine rocks carrying this finely distributed gold. Within the last 10 years, large volumes of ground were excavated to remove gold ore, forming a large open pit as shown in the photograph to the left. Gold ore was placed in one pile, and rock that did not contain gold was put into waste piles. To remove the gold, the ore pile was sprayed with a mixture of water and cyanide, which dissolved the minute gold grains. Further chemical treatment of the cyanide solutions caused the gold to separate. The gold was then collected, formed into bars, and sold. In 1992, mining ended at Summitville because most of the gold ore had been removed and the ore remaining was unprofitable to mine. The large open pit was abandoned, and rocks in the ore pile and waste piles remained in place.

Many of the rocks remaining in the rock piles, open pit, and underground tunnels contain sulfides, especially pyrite, that undergo chemical reactions when they come into contact with air and rainwater at or below the ground surface. This process is called chemical weathering. During chemical weathering, air and rainwater react with sulfide minerals such as pyrite, enargite, chalcopyrite, covellite, and chalcocite and generate large amounts of sulfuric acid. The altered rocks, which formed by an earlier episode of corrosion by sulfuric acid, as described previously, cannot neutralize the acid formed by chemical weathering. The acid dissolves many heavy metals present in ore and non-ore minerals to produce a fluid-acid mine drainage. The Summitville mine drainage waters are among the most acidic and metal bearing in Colorado; the drainage waters have a pH generally below 3 and contain high to extreme concentrations of iron, aluminum, copper, zinc, arsenic, lead, and other metals.



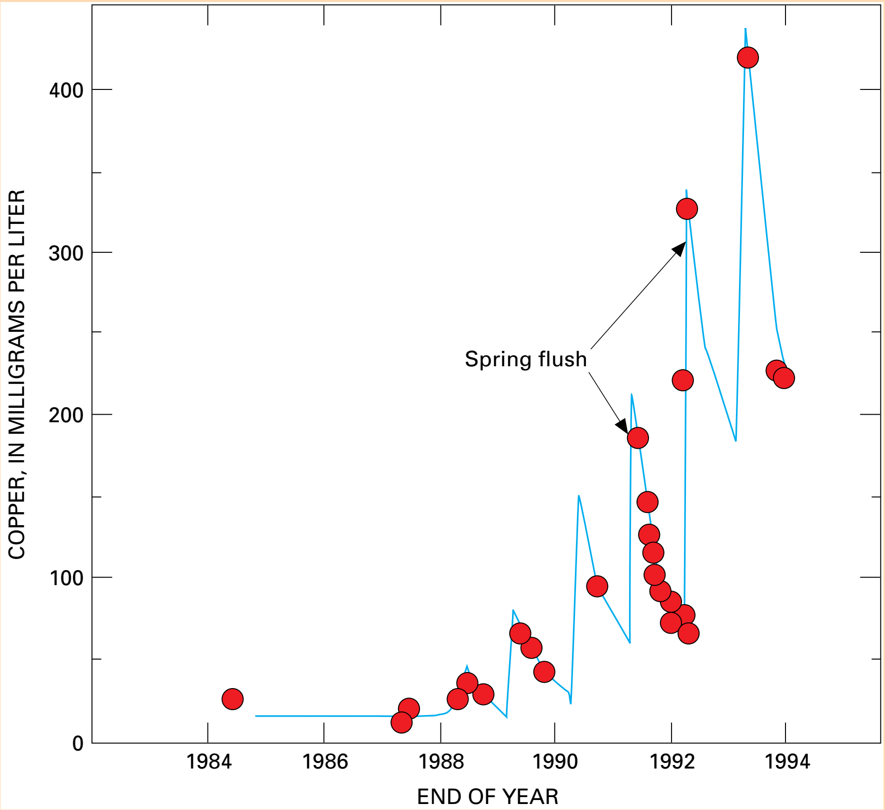
Production of sulfuric acid by the reaction of pyrite with air.



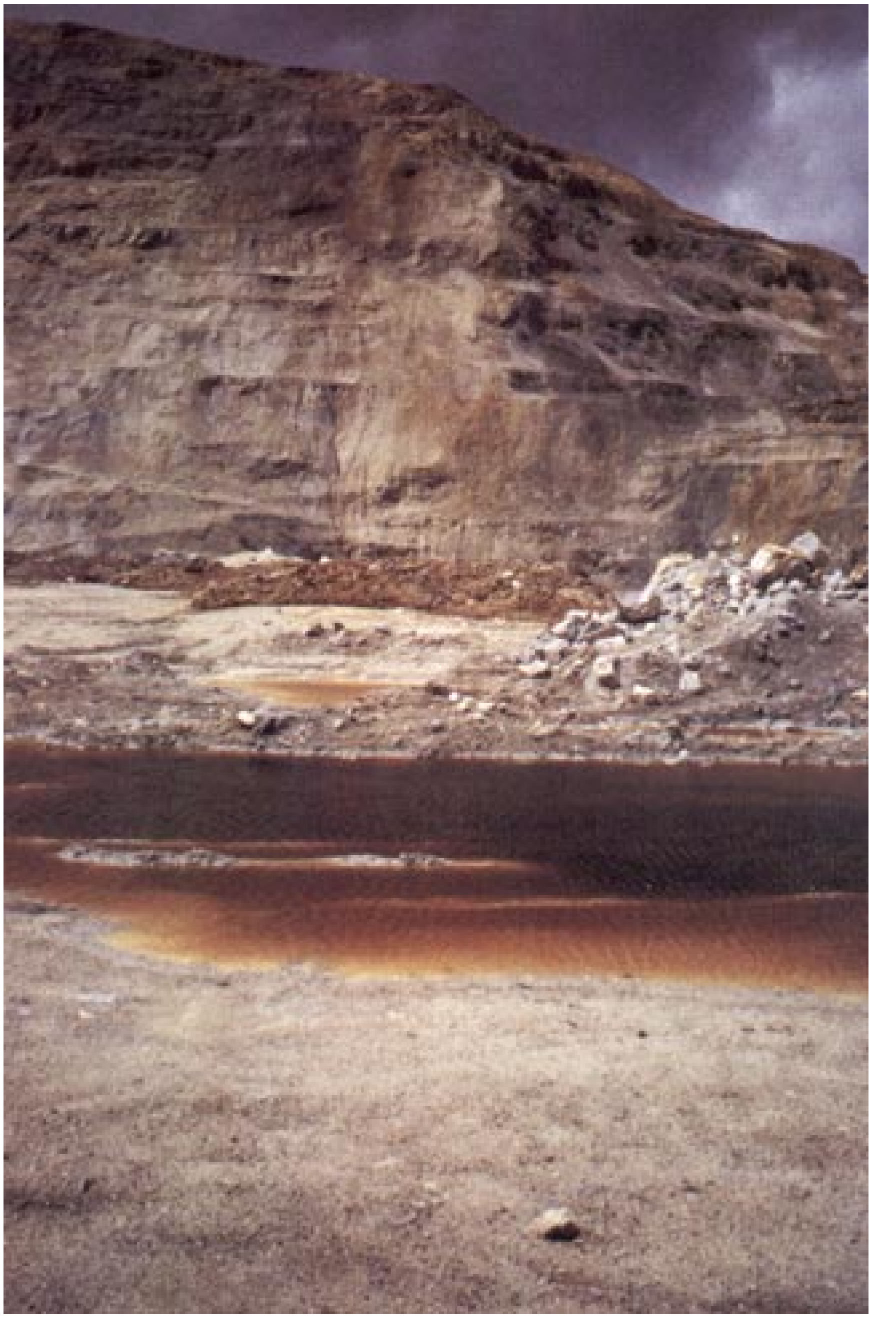
pH and heavy-metal composition (zinc, copper, cadmium, lead, cobalt, and nickel) at the Summitville mine site and other mine areas in Colorado.

As a result of mining activity, the content of copper and other metals in waters draining the Summitville pit via underground workings and the Reynolds adit significantly increased from 1984 through 1993. During dry periods, acid mine waters evaporate from the underground mine workings, mine waste dumps, and fractured rock around the open pit. As the waters evaporate, they leave behind abundant metal-bearing salts such as chalcanthite, a copper sulfate mineral. These salts store acid and metals in the solid form, and they are highly soluble and redissolve when the next pulse of rainwater or snowmelt flows through the mine.

The resulting flush of these salts can lead to sharp, short-term increases in acid and metals draining the site, such as the seasonal spike in dissolved copper concentration in Reynolds adit outflow that coincides with spring snowmelt (as shown in the photograph on this page). Deep red puddles that are highly acidic and metal rich form soon after summer thundershowers (as shown in the photographs on the facing page). These puddles also reflect the dissolution of soluble metal salts in the pit rocks. Extensive remedial efforts will be required to isolate both unweathered sulfides and soluble metal salts in the open-pit area and in mine waste piles from weathering and dissolution.

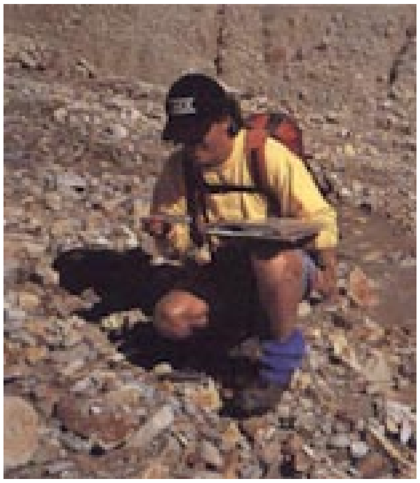


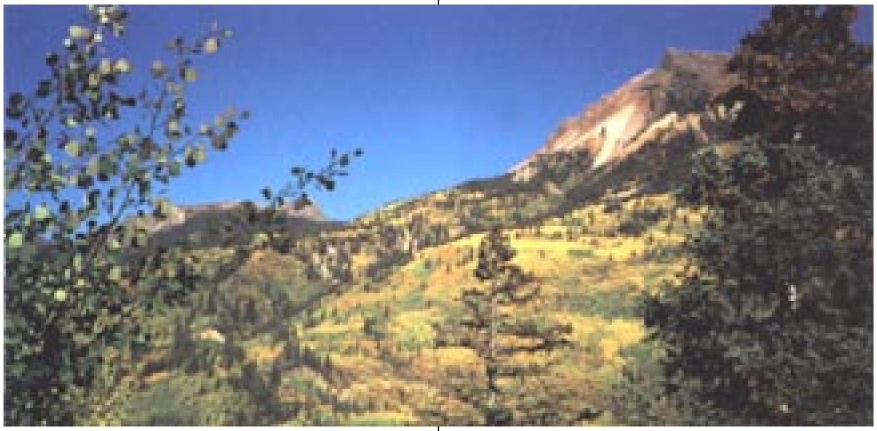
Amount of copper in the Reynolds Tunnel outflow over time. Modified from Golder Associates (1992).



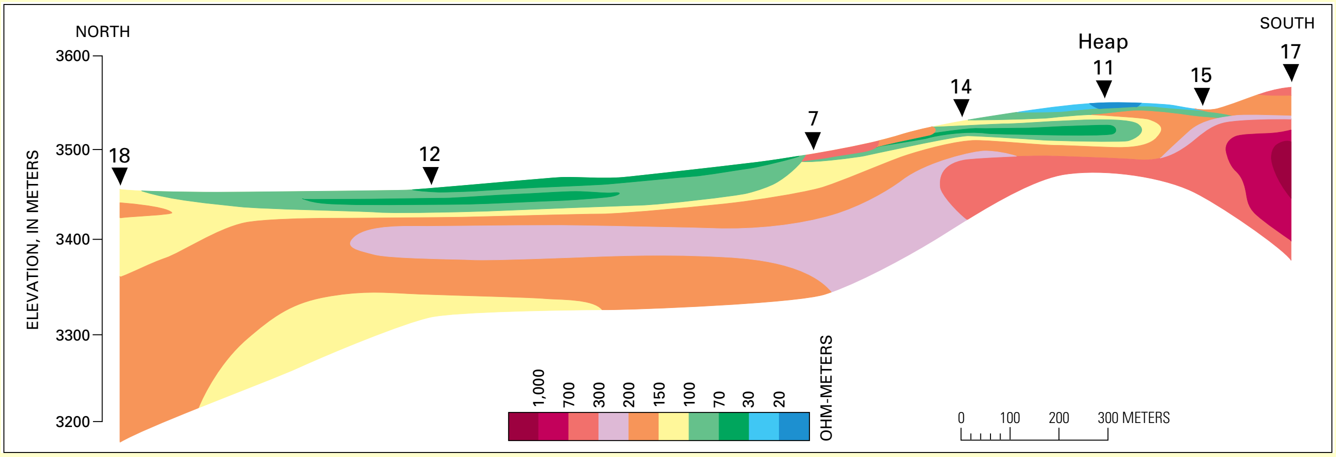
GEOPHYSICS PLAYS A ROLE IN UNDERSTANDING ACID MINE DRAINAGE

Not all water in the Summitville area moves along the ground surface. Some water flows beneath the surface and may re-emerge in springs, creeks, and rivers. How can we see the geologic structures and movement of fluids that are hidden from our direct view? One important aid is the geophysical technique called electrical resistivity. Rocks do not conduct electricity very well; they resist the flow of electricity. The most resistive rocks are dense (low-porosity) materials such as granite, limestone, or some crystalline volcanic rocks. Moderately resistive material includes porous sand and gravel that is saturated with potable water. Low resistivity commonly indicates highly altered or fractured rocks, rocks filled with nonpotable water, or clay-rich rocks.





How can we make these resistivity measurements and interpret the results? The basic technique is to "shock" the underground rocks by introducing an electric current of known voltage at a specific point. The current flows through the rocks, but not very efficiently, and sensitive electrodes placed at several other locations measure the change in voltage. This voltage decrease is a reflection of the resistivity of the rocks and fluid in the subsurface and can be interpreted in terms of rock mineralogy, water content, and water quality. In a homogeneous rock the current flows equally in all directions; however, if the rock is not homogeneous the flow of the current is modified, and differences in resistivity can be mapped. Complications can arise, however, if manmade (cultural) materials are present that can affect the measurement of underground resistivity. For example, at Summitville, power lines, metal structures and debris, cables, and pipe lines are all detrimental to accurate measurements. The Schlumberger sounding method has been developed to lessen both these types of cultural problems and lateral variations in resistivity. In this method, computer models are developed using a series of horizontal rock layers of known resistivity and are compared to the measured resistivities in order to determine the closest fit to the data. This method was used to map the subsurface in the Summitville mine area.



Geoelectrical cross section through the heap-leach pile at the Summitville mine. Triangles represent the surface locations of the soundings.

A number of individual soundings can be combined to create a resistivity cross section. Cross sections, which can be thought of as vertical slices through the ground similar to road cuts, are more easily interpreted than individual soundings and illustrate lateral as well as vertical variations of resistivity. For illustrative purposes in the figure showing a cross section through the heap-leach pile (sounding 11), warm colors (orange-red) represent high resistivities, and cool colors (blue-green) represent low resistivities. The cross section demonstrates that the heap-leach pile (indicated by yellow and green) is located on the volcanic andesite (an extrusive rock that formed when the magma from the volcano flowed on the surface), which in turn lies upon some of the oldest rocks in the area (commonly dense and nonporous rocks known as basement rocks) represented by the higher resistivities (pink and red colors). At soundings 15 and 17, high resistivities indicate that the basement rocks are only 40 meters below the surface and extend under the heap-leach pile to near sounding 14.

Downward movement of mine drainage through the subsurface is probably hindered wherever the fluids encounter basement rocks; the mine drainage then flows along the basement surface downhill to the Wightman Fork. The basement rocks probably dip to the north, mimicking the topographic surface, and they may represent an erosional surface that is buried beneath the younger volcanic rocks. To the north (under sounding 12), in the suggested direction of fluid flow, low-resistivity rocks are 20–30 meters below the surface and probably represent clay-rich or water-saturated sediments.

When evaluating the movement of acid mine drainage in the Summitville mine area, we must understand the flow of fluids through both the surface and subsurface because both types of flow influence the amount, direction, and quality of the discharge.

SUMMITVILLE FROM THE AIR

Remote sensing data of the Summitville mine site and adjacent areas were collected using NASA's Airborne Visible and Infrared Imaging Spectrometer (AVIRIS) system.

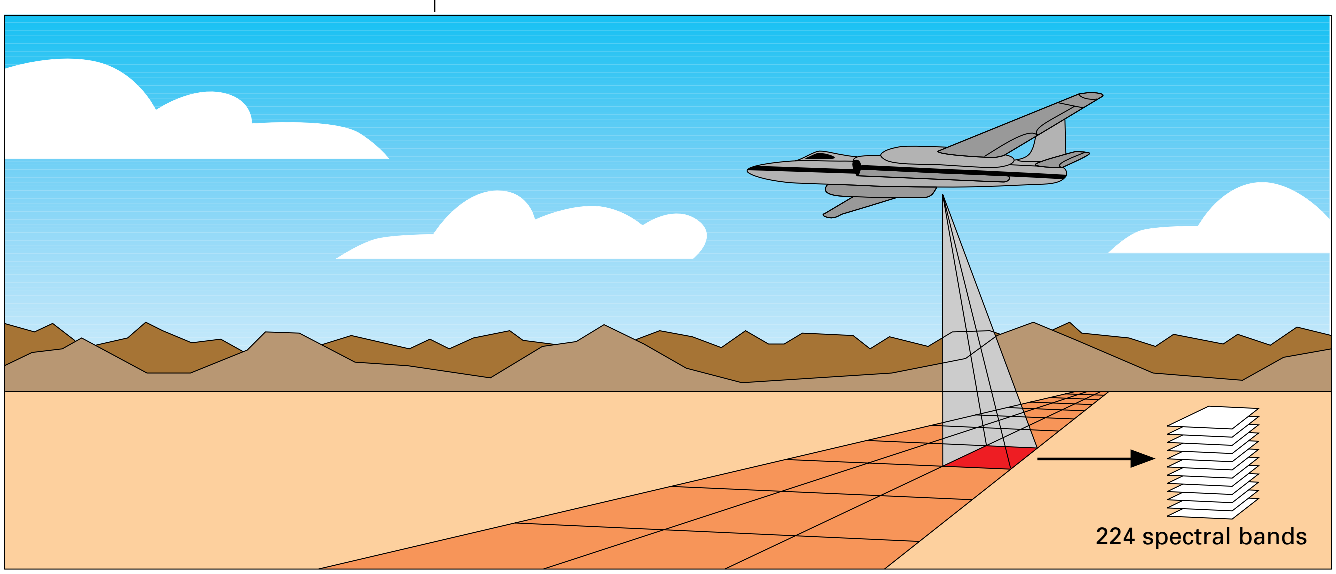
The AVIRIS system is a NASA (National Aeronautics and Space Administration) instrument onboard an aircraft flown at about 19,800 meters altitude at speeds of just less than mach 1 (the speed of sound). The data are collected to provide an image of the land surface across a swath about 11 kilometers wide.

The image is composed of many data points, called pixels. Each pixel is a three-dimensional data point consisting of an X, Y, and Z component. Each pixel represents a surface area (the X and Y components) of about 17 meters by 17 meters and contains information on the chemical and mineralogical character of the material (the Z component). Spectra acquired by remote measurements are interpreted by comparison with laboratory spectra from known samples.

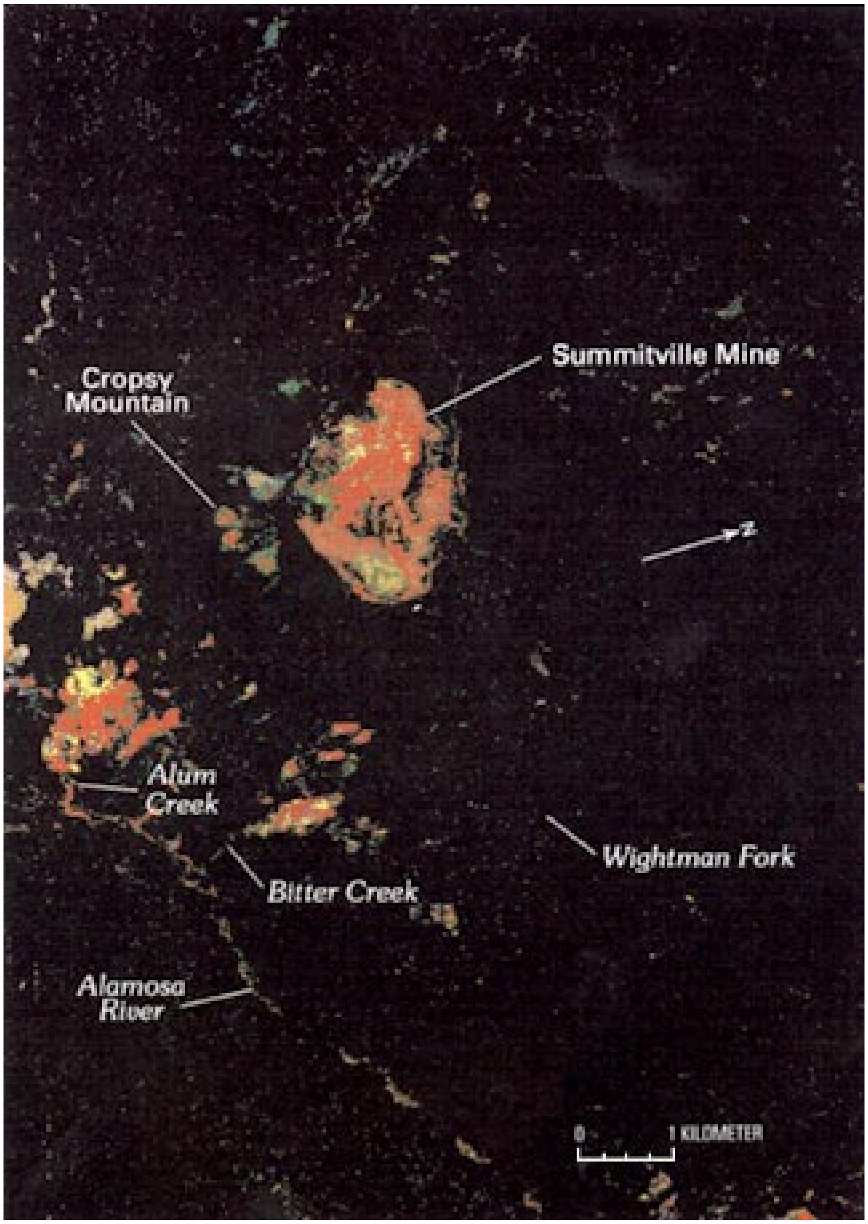
Imaging spectroscopy data of the Summitville mine and the Iron, Alum and Bitter Creek basins were used to search for minerals associated with alteration. USGS scientists produced maps using the continuous spectral coverage data to define the distribution of these mineral groups. Hydroxyl-bearing materials, including clays, show discrete distribution boundaries at both the mine site and within the Iron, Alum, and Bitter Creek basins.

Remote Sensing

Most naturally occurring and manmade materials absorb sunlight at specific wavelengths. For example, it is the absorption and scattering of the sunlight by plants that produces the green color observed by the human eye. Just as every human has a characteristic thumb print, each mineral and manufactured material has a unique spectral signature related to its chemical composition, grain size, degree of crystallinity, and temperature of formation. The spectral signature is a measure of how reflected sunlight interacts with a surface. Spectral information can be gathered from laboratory measurements, or it can be remotely acquired by aircraft or satellite systems, therefore providing a powerful mapping tool.



Imaging spectroscopy data are acquired from an aircraft, in this study using the AVIRIS system of NASA. The aircraft acquires data over a swath about 11 kilometers wide. The image is composed of a series of three-dimensional data points or pixels that sense a 17-meter by 17-meter area on the surface (the X and Y directions) and acquire a solar reflectance spectrum in the Z direction.



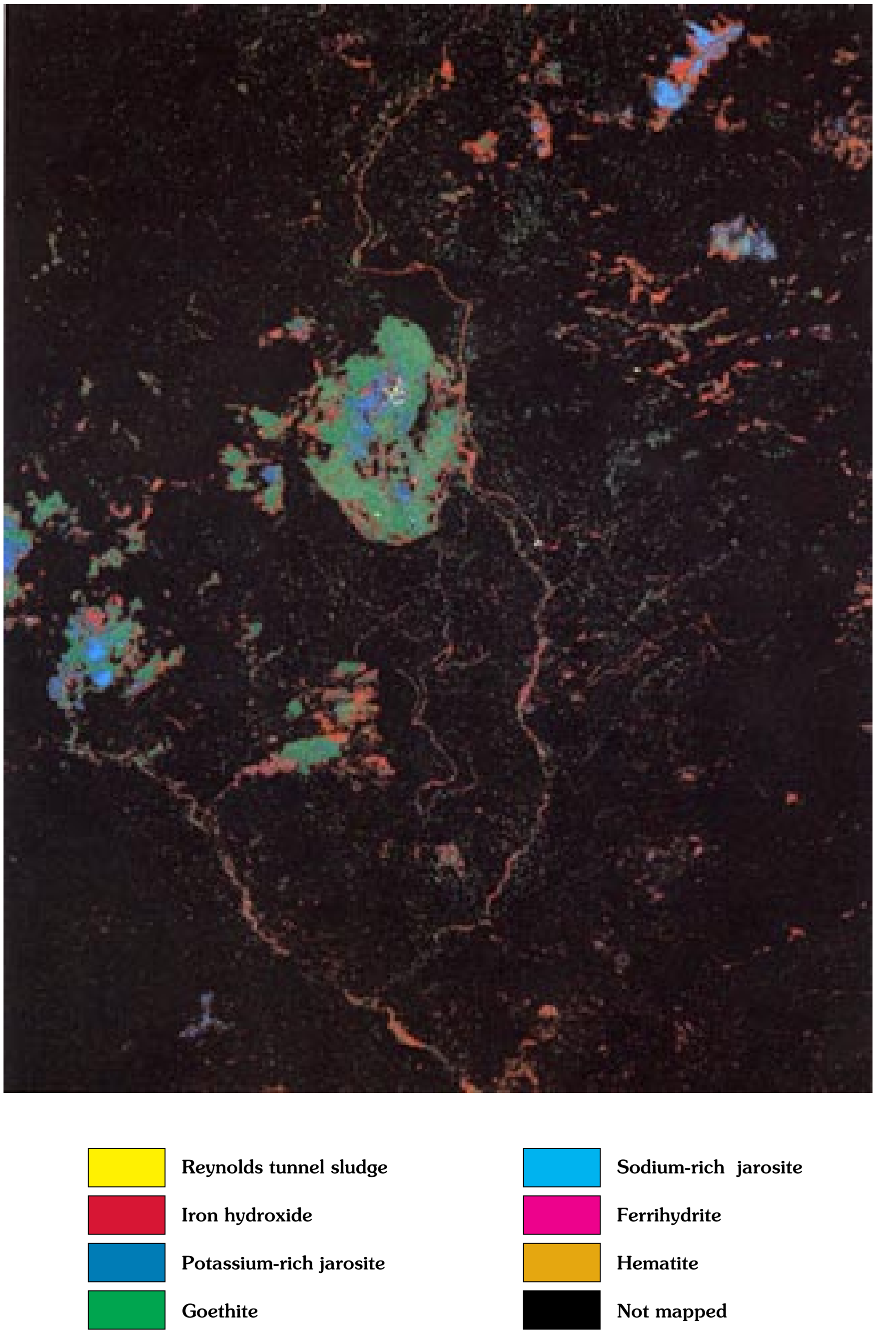
- Halloysite or kaolinite-smectite mixture
- Potassium-rich alunite
- Sodium-rich alunite
- Poorly crystalline kaolinite
- Highly crystalline kaolinite
- Sodium-rich montmorillonite
- Not mapped

AVIRIS image of the Summitville mine and adjacent area showing the distribution of hydroxyl-bearing minerals. Image made September 3, 1993.

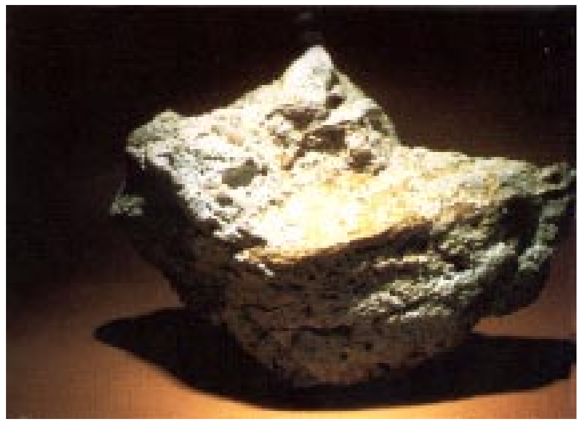
Perhaps the most interesting observation from the spectral data is that the Summitville mine apparently does not contribute hydroxyl-bearing minerals via the Wightman Fork to the Alamosa River, in contrast to the mineralized areas in Iron, Alum, and Bitter Creek basins, which do. This observation is based on the spectral characteristics of the exposed fluvial sediments along Alum Creek and Bitter Creek and the lack of hydroxyl-bearing fluvial sediment along the Wightman Fork. The unmined mineralized areas are believed to contribute hydroxyl-bearing materials to the Alamosa River because of the porous character of the well-exposed rock, which allows altered materials to be eroded easily and deposited along the streambanks as sediment. If hydroxyl-bearing materials, and associated contaminants, are being supplied to the Wightman Fork by the Summitville mine, the material must be carried as a very fine grained aqueous suspension in the water, which cannot settle on the creek banks.

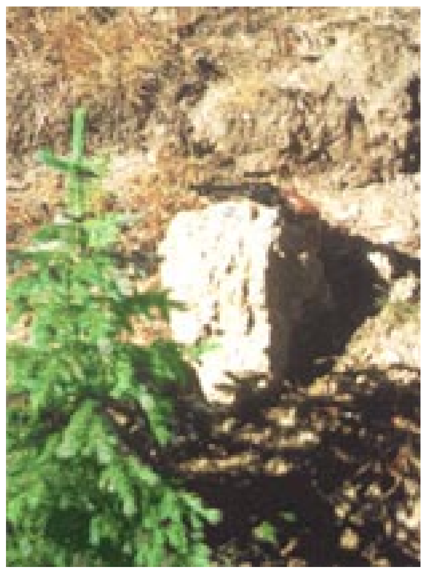
Images show that both the Summitville mine and the Iron, Alum, and Bitter Creek basins are sources of iron-bearing sediments to the Alamosa River. These sediments give a reddish-brown color to streambanks, a characteristic typically associated with acid drainage, and are potential carriers of heavy metals to locations downstream. Consequently, in assessing the environmental impact of mining at Summitville, it is an important observation that both the Summitville mine site and the Iron, Alum, and Bitter Creek basins contribute this type of sediment to the Alamosa River.

Downstream from the Summitville mine, other creek drainages, including the Jasper area, contribute hydroxyl-bearing and iron-bearing minerals to the Alamosa River. These river sediments are then carried into the Terrace Reservoir (shown below), the source of irrigation water for some parts of the San Luis Valley.



AVIRIS image of the Summitville mine and adjacent area showing the distribution of iron-bearing minerals. Image made September 3, 1993.





WATER TRANSPORT— A POWERFUL WAY TO MOVE METALS

Water Quality

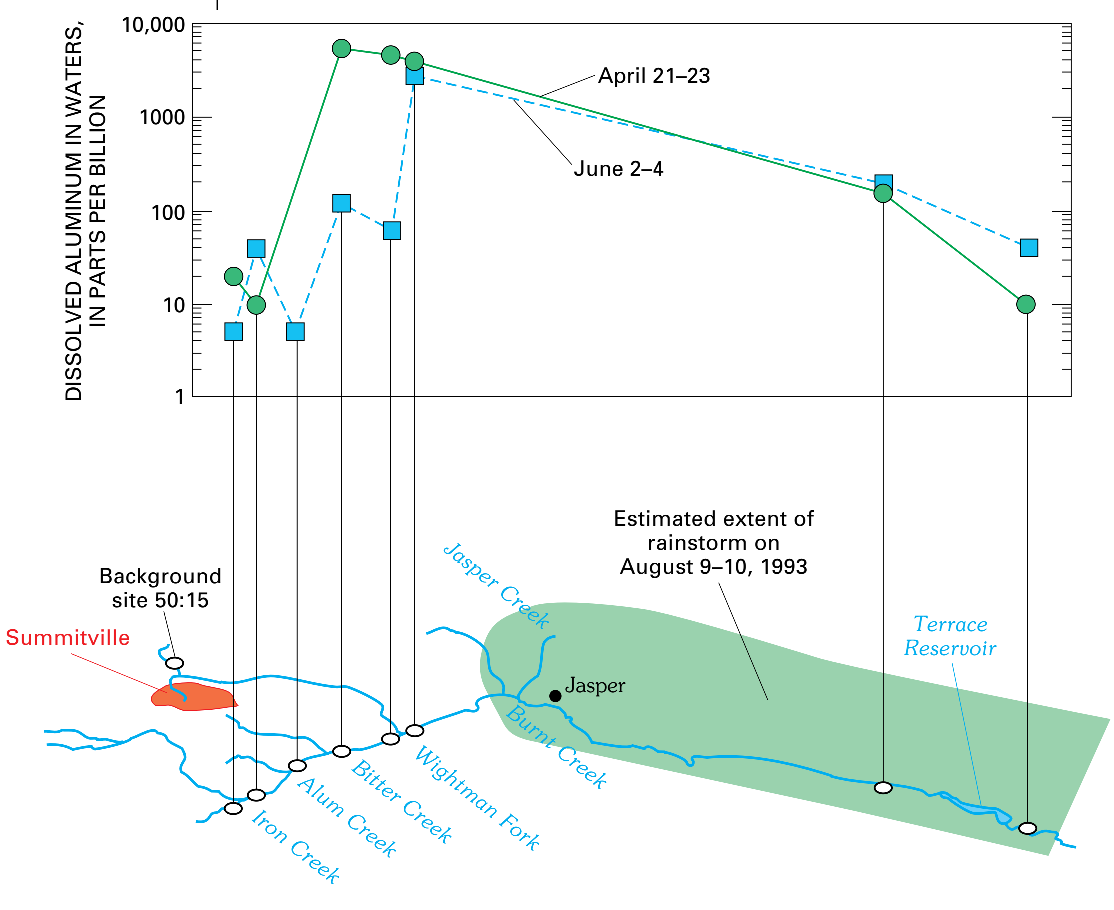
Water quality is determined by the amounts of suspended solid particles and dissolved substances. Federal and State agencies provide standards for water quality based on whether the water will be used for (1) recreation, (2) aquatic life, (3) agriculture, or (4) domestic supply. The standards are in the form of tables of maximum allowable concentrations for a wide variety of elements and organic compounds.

Drainage from the Summitville mine comes from three sources—heap-leach water, seeps that are present throughout the mine workings, and water coming from the old Reynolds adit. These waters move downslope into Wightman Fork, a small tributary of the Alamosa River, which in turn flows east for about 24 kilometers and then enters the fertile agricultural lands of the San Luis Valley. The increase in the trace metal burden of the Alamosa River watershed due to mining activity at Summitville is of concern to farmers, fishermen, and Federal and State of Colorado agencies.

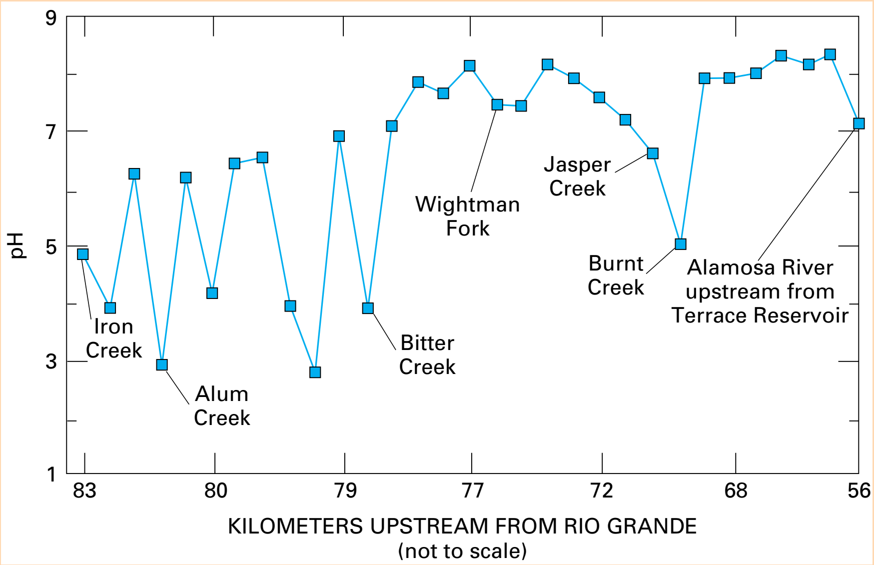
To investigate the influences of waters containing heavy metals on the surrounding region, the USGS initiated a study of local and regional water quality.

Between April and September 1993, in the Alamosa River and the Wightman Fork, water samples were collected to determine their quality and water discharge rates were measured. These data were used to evaluate the impact of the Summitville mine on water quality in the river basins and in Terrace Reservoir and to locate sources of acidic waters containing elevated concentrations of aluminum, copper, iron, manganese, and zinc.

Metal concentrations are higher and pH values lower (more acidic) in water immediately downstream from the Summitville mine site relative to water collected just upstream from the mine (the background site). This observation indicates that



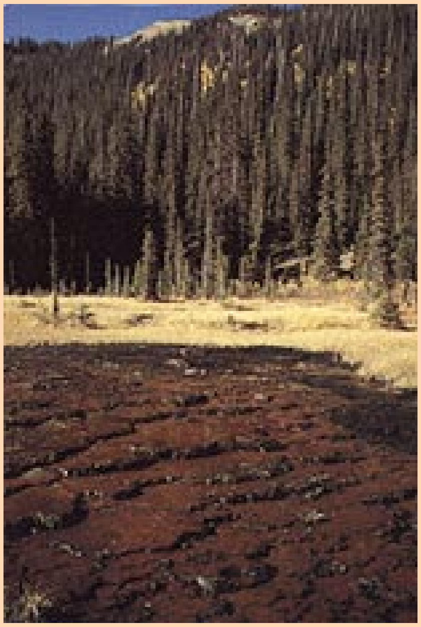
Concentration of dissolved aluminum along the Alamosa River during April and June 1993. The geographic extent of the rainstorm discussed on page 21 is also shown.

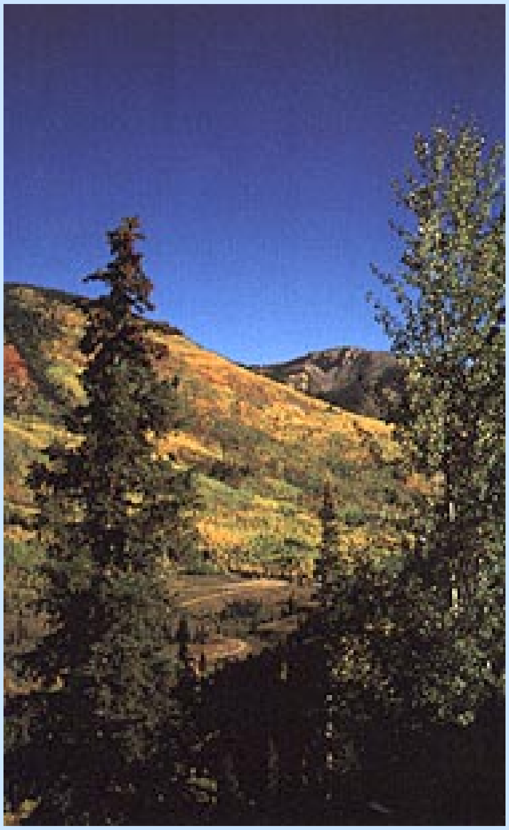


pH of inflows along the north side of the Alamosa River, May 6, 1993. Station locations are measured from the confluence of the Alamosa and the Rio Grande Rivers in the San Luis Valley.

acidic, metal-rich water may enter the Wightman Fork in its headwater region upstream from either where the background stream enters the Wightman Fork or where it crosses the mine site. There is some input of metals and low pH water to the Alamosa River upstream from the Wightman Fork during the first part of spring snowmelt runoff (April through May). Numerous small tributaries upstream from the Wightman Fork contribute acid water to the Alamosa River at this time. Many of these tributaries stop flowing when snowmelt ends. During the late April sampling trip, concentrations of dissolved aluminum were greater upstream from the Wightman Fork than in the Wightman Fork. During all other sampling trips, concentrations of dissolved aluminum were lower upstream than in the Wightman Fork. Data for iron concentrations show a similar trend. Therefore, during early snowmelt in April, sources upstream from the Wightman Fork are the primary cause of elevated aluminum and iron concentrations in the Alamosa River.

By measuring both the total concentration of an element carried in water and the water flow rate, it is a simple matter to calculate the amount of an element transported during a fixed-time interval. This calculation was performed for the Wightman Fork and the Alamosa River upstream from the Wightman Fork for eight fixed-time periods. Ratios of the amount of metal in water from the Wightman Fork to the amount of metal in the Alamosa River are shown in the table on the following page. Values greater than 1 indicate that Wightman Fork is the major contributor of that metal to the Alamosa River. Values less than 1 indicate that sources other than and upstream from the Wightman Fork are the major contributors of that metal to the Alamosa River. The Wightman Fork is the source of most of the copper, manganese, and zinc discharged into the Alamosa River and Terrace Reservoir during all sampling periods and is the primary source of aluminum and iron during the latter parts of spring



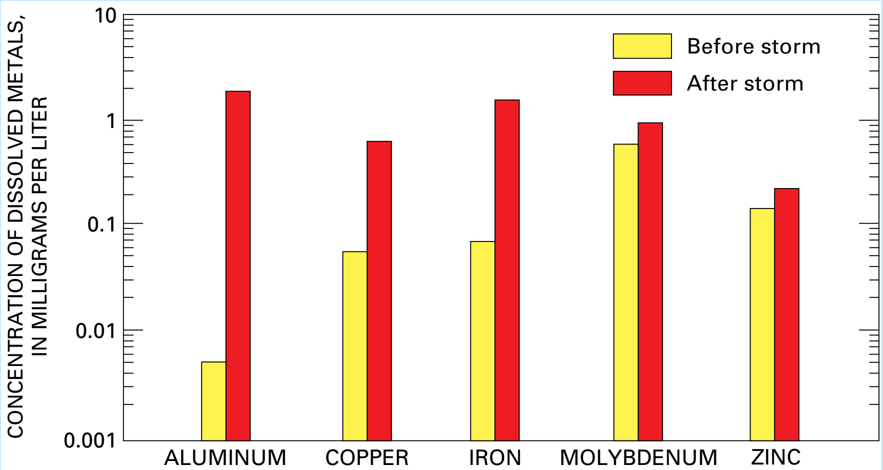


Ratio of total amount of metal in the Wightman Fork at its mouth to total amount of metal in the Alamosa River above Wightman Fork

[A ratio of more than 1 indicates that the Wightman Fork supplies most of the metal to the Alamosa River, and a ratio of less than 1 indicates that areas upstream from the Wightman Fork supply most of the metal to the Alamosa River]

Date	Aluminum	Iron	Copper	Manganese	Zinc
April 21–23, 1993	0.24	0.10	16	1.1	1.8
May 4–6, 1993	0.27	0.15	7	1.3	1.5
May 18–20, 1993	1.3	0.85	47	4.1	11
June 2–4, 1993	3.0	2.8	230	6.4	15
June 21–23, 1993	1.7	2.4	340	4.6	>26[1]
July 12–14, 1993	2.0	1.9	330	4.6	16
August 8–10, 1993	1.1	0.39	62	3.6	9.6
September 7–8, 1993	0.71	0.36	53	3.2	5.9

[1]The amount of total recoverable zinc in the Alamosa River above Wightman Fork is below the detection limit of 10 micrograms per liter.



Concentrations of dissolved metals in the Alamosa River upstream from Terrace Reservoir before and after a rainstorm, August 10, 1993. The geographic extent of the rainstorm is shown on page 20.

runoff and into July and August. Sources upstream from the Wightman Fork supplied most of the iron and aluminum to the Alamosa River in April, early May, and September.

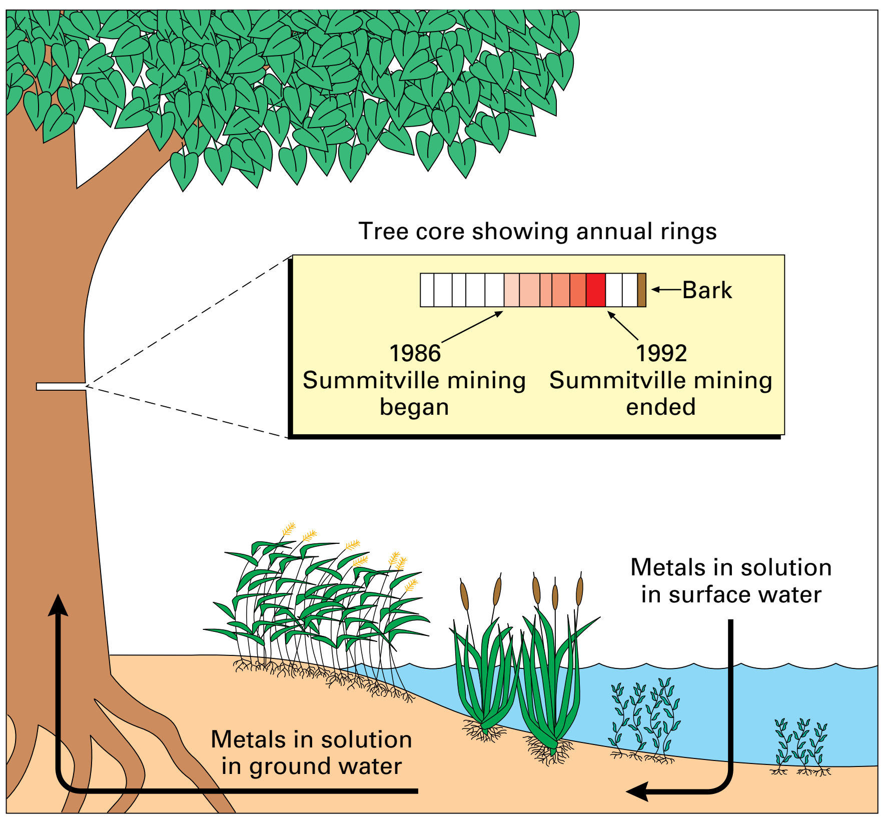
A few tributaries downstream from the Wightman Fork, including Burnt Creek, contribute acidic, metal-bearing water to the Alamosa River during the early part of snowmelt runoff. This observation was confirmed in an unusual manner during August 1993. Samples were collected in the Alamosa River directly upstream from Terrace Reservoir before and after a rainstorm that soaked an area downstream from, but not including, the Wightman Fork drainage basin. Runoff from the storm had two important effects. First, water flow rate in the Alamosa River increased by a factor of three. Second, concentrations of some metals in the Alamosa River upstream from Terrace Reservoir increased as many as 400 times.

Sources of acidic, metal-rich water to the Alamosa River include (1) areas that have been disturbed by mining, such as Summitville, and (2) areas that have had minimal mining activity but where the rocks are hydrothermally altered, such as Iron, Alum, and Bitter Creeks, upstream from the Wightman Fork and Burnt Creek, and downstream from the Wightman Fork. Many natural sources of acidic water were identified in these altered areas.

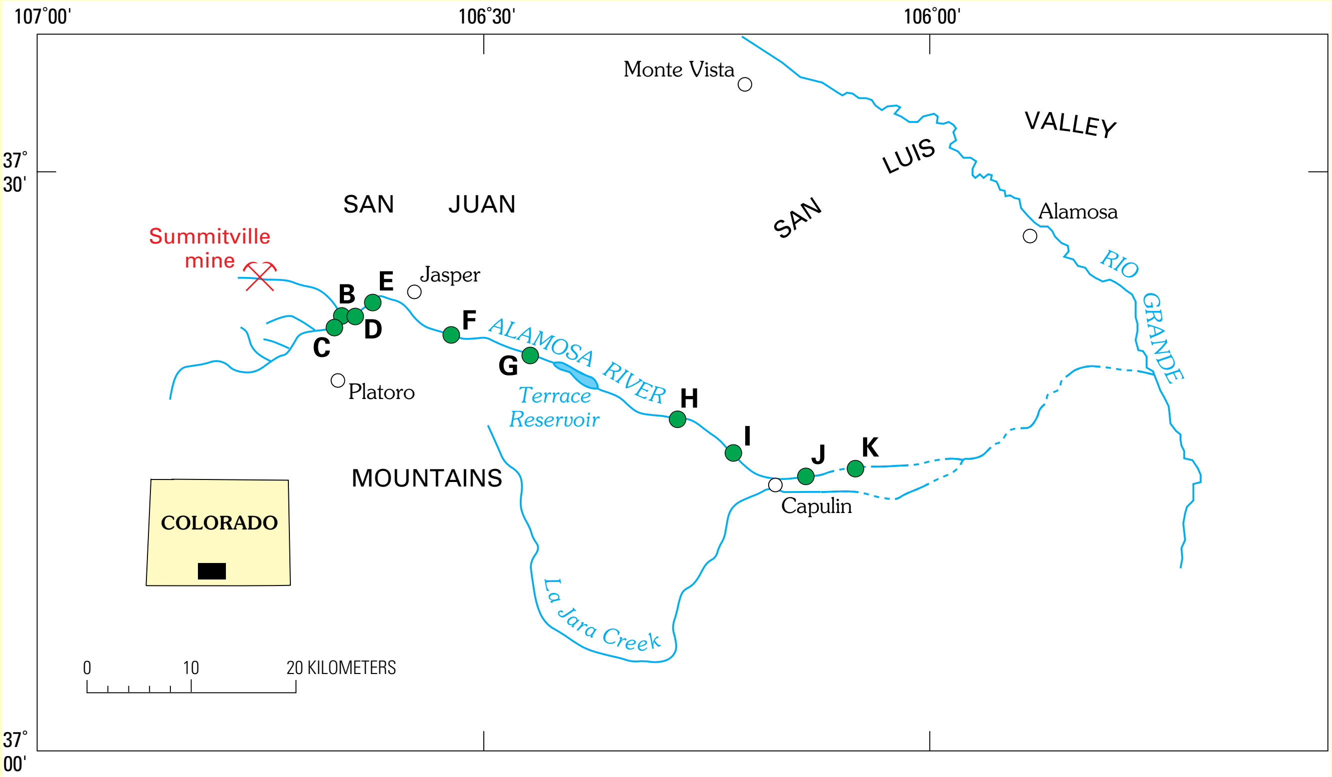
REVEALING GROUNDWATER QUALITY BY EXAMINING TREE RINGS

Tree rings are used by geologists to examine past environments. They are particularly useful because each ring represents one year of growth, preserving evidence of past conditions. Counting rings from the outside toward the tree center allows the researcher to move precisely backward in time. Nutrients provided by the root system are required by a tree in order to promote ring growth. The roots excrete acids that then dissolve metals in the soil, making them available for uptake by the tree. These metals eventually are deposited within the growing tree. Consequently, small changes in soil chemistry can be seen by examining the metal concentrations in tree rings, and these changes can be precisely dated.

The use of plants in assessing environmental metal contamination has a long history. In the middle of the 19th century, the association was made between overall air quality in heavily industrialized European cities and the presence or absence of specific species of tree lichens and mosses. Both tree lichen and mosses are capable of absorbing large quantities of metals, and recently the USGS has used them to establish baseline levels for metals in plant tissues. These plants have also been used to map regions of greater metal concentrations associated with contaminants emitted into the atmosphere from specific point sources such as smokestacks of power-generating stations or mine sites.



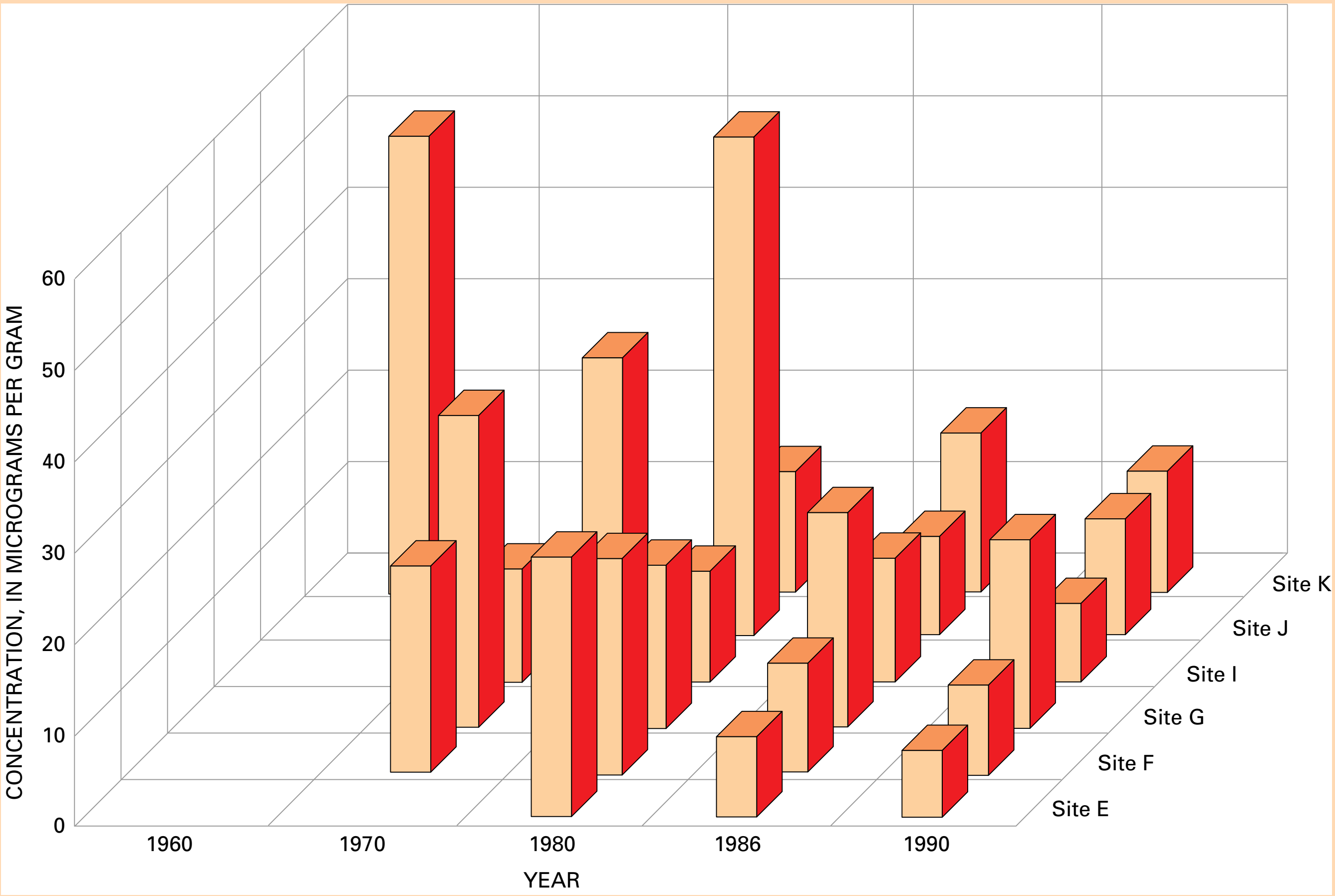
Metal levels in individual annual rings of cottonwood can be examined for differences between years (pre-mining versus post-mining) or between the same year but at various distances from the Summitville mine. The latter is an indirect measure of the efficiency of metal transport in the Alamosa River system.



Tree-ring sampling sites along the Alamosa River.

Tree-ring studies are useful, but the chemistry of tree rings can be difficult to interpret. First, there may be differences in metal concentrations around the perimeter of a single tree ring. Second, metals may move between rings, particularly if there are initially large differences in concentrations between adjacent rings. Third, narrow tree rings, representing a slow growth rate, make ring-counting more difficult and add errors to the dating. Fourth, distinguishing between local and distant metal sources is difficult. Despite these problems, tree rings have been used successfully to document changes in groundwater chemistry down gradient from point sources of metal contamination.

Near Summitville, in the Alamosa River basin, the USGS analyzed individual tree rings from narrow-leaf

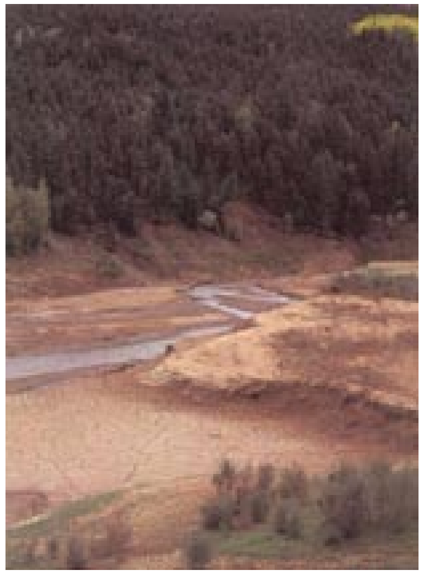


Zinc concentrations in cottonwood tree rings downstream from the Summitville mine along the Alamosa River. Scientists can examine differences within a single tree over time, as well as differences between sites for specific years.

cottonwood (*Populus angustifolia*) and aspen (*Populus tremuloides*). Both types of trees produce annual growth rings that can be precisely dated. Small cores were drilled from the outside toward the center of each tree and extracted for analysis. Individual tree rings were analyzed using a new analytical instrument, a laser-ablation inductively coupled plasma mass spectrometer (LA-ICP-MS).

Both copper and zinc, heavy metals that are environmentally hazardous, were detected in the rings of the tree samples. Both metals are most abundant in older tree-ring tissue formed prior to mining activity at Summitville. Thus, the amount of copper and zinc available to the tree roots has decreased in recent years. This distribution may be due to an absolute decrease in levels of copper and zinc in the soils; however, high concentrations of copper in groundwater produce toxicity in tree roots, retarding metal uptake. Consequently, the decrease of copper and zinc in the tree rings may reflect toxicity as a result of increased copper and zinc levels in the soil. More study is required to distinguish between these competing interpretations.

Molybdenum, an element associated with the Summitville mineralization, was also detected in the tree rings. The data for molybdenum suggest that its presence in the tree rings decreases as the distance from the Summitville mine increases; however, the amount of molybdenum observed does not change on a yearly basis. There was, however, an increased uptake at site K, possibly due to oxygenated, saline soil conditions that favor molybdenum uptake by plants. Bromine is also more abundant in the older tissue relative to the newer tissue but does not decrease in abundance as a function of distance from the Summitville mine.



Tree-Ring Chemistry

Laser-ablation inductively coupled plasma mass spectrometer (LA-ICP-MS) has the capability of determining the concentrations of about 50 elements in tree rings at the parts per billion level in an area of the ring that has a diameter as small as a pencil dot. The tree-ring core is viewed through a microscope, and individual rings are burned by a fine laser beam. The resulting gaseous plasma is then heated, and metal concentrations are measured using a very sensitive mass spectrometer.

PATHWAYS OF SEDIMENT AND WATER TO THE SAN LUIS VALLEY

Acidic, metal-bearing surface water and sediment carried down the Alamosa River enters Terrace Reservoir. From Terrace Reservoir, the Alamosa River runs east through the Alamosa National Wildlife Refuge. Because the San Luis Valley is a major agricultural center for Colorado, analyzing the effects of these waters and sediments on crops and livestock is of particular concern to local farmers and agricultural industries. Similar concerns are also relevant to the Alamosa Wildlife Refuge, a sanctuary for migrating birds including sandhill and whooping cranes.

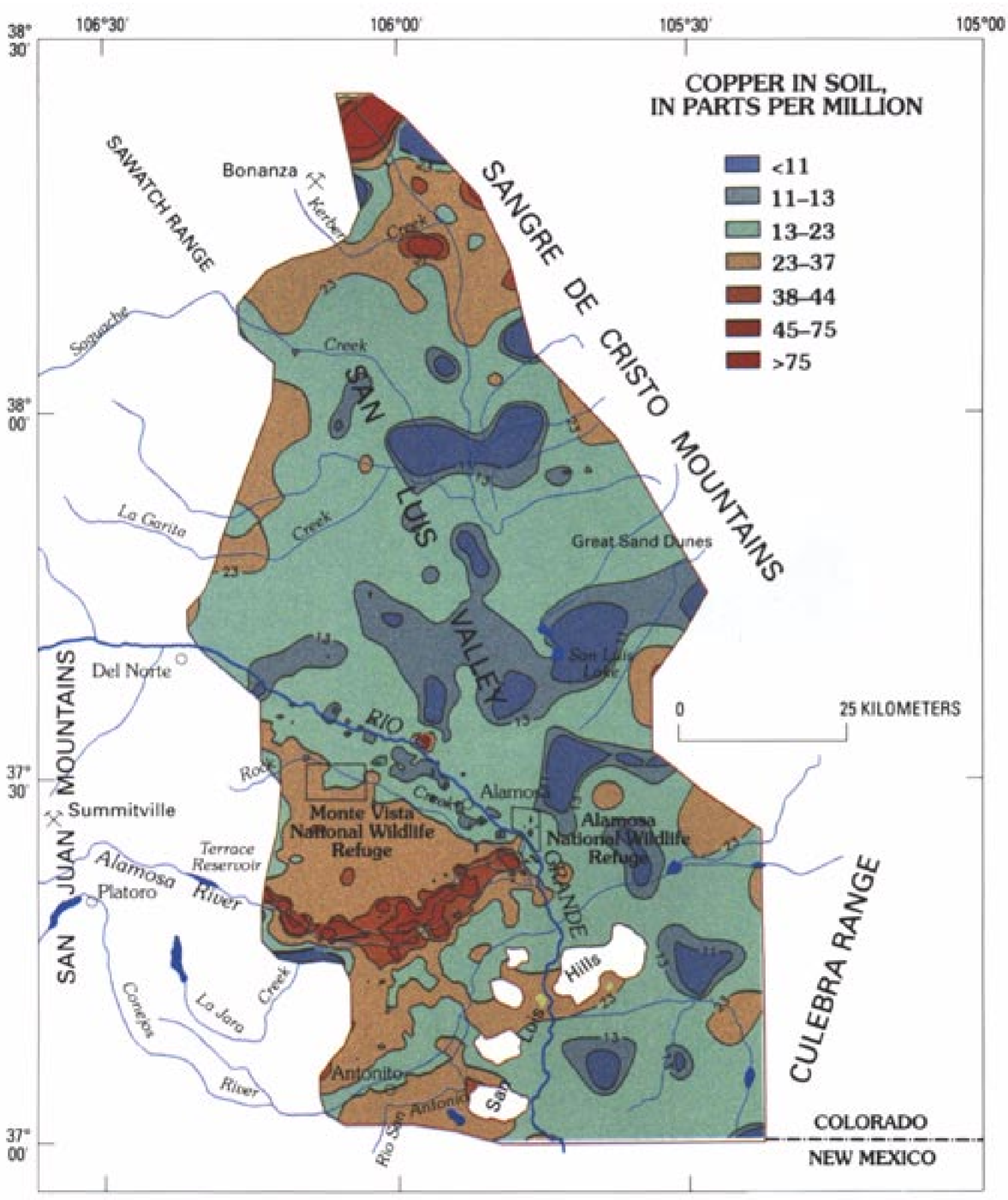
Weathering breaks rocks into particles and dissolved forms that are readily transported. Streams, the most common mode of transport, are the most effective way to move sediment, especially near their headwaters where they move fastest. Material is transported downstream until the carrying capacity of the stream diminishes, the water slows down, and solid particles are deposited to form sediments. Some sediments form directly in the streambed, whereas others are deposited over the streambank as a result of flooding. After floodwaters recede, these overbank sediments are further weathered to form soils. Thus, the particular mixture of minerals in the soil reflects the mineralogy of the source rocks and imparts a geochemical fingerprint to the soil. Where the source rocks have a geochemically unusual signature, such as in an area where ore deposits are present, the signature of the soil commonly is similar to that of the ore deposits.

Examination of the rivers and streams that flow into the San Luis Valley indicates that the major sources of sediment are the Sangre De Cristo Range, the Sawatch Range, and the San Juan Mountains. Most of the sediment results from the weathering and erosion of volcanic rocks. These source areas also include a number of ore deposits, some of which have been mined, and therefore it might be expected that sediments enriched in heavy metals are also carried into the San Luis Valley and become part of the soil. Chemical analysis of soils collected by the USGS in this region in 1993 indicates that two major mining districts, Summitville and Bonanza, contribute metal-bearing sediment to the San Luis Valley floor. The Bonanza mining district introduces sediment into the northern part of the valley. Sediment is carried to the southern part of the San Luis Valley floor via numerous streams, including the Wightman Fork, the Alamosa River, and the Rio Grande River. The Rio Grande River does not carry sediment derived from the Summitville mine or directly adjacent areas, whereas the Wightman Fork and the Alamosa River do.

Rock Weathering

How long does a rock last? The primary mechanism of erosion is weathering. The severity of weathering depends on climate, original rock composition, and time. Given sufficient time, climate is the dominant factor. Weathering is a twofold process. Mechanical weathering, the shattering of rocks, results from the physical action of water, ice, wind, and gravity, which causes rocks to fragment. Chemical weathering, the chemical decomposition of rocks, results from the corrosive action of water, which causes parts of the rock to be dissolved.

The Sawatch Range and the Bonanza mine contribute sediments containing copper to the northern part of the San Luis Valley, and the Rio Grande and Alamosa River carry sediments to the southern part of the valley.


COPPER IN SOIL, IN PARTS PER MILLION
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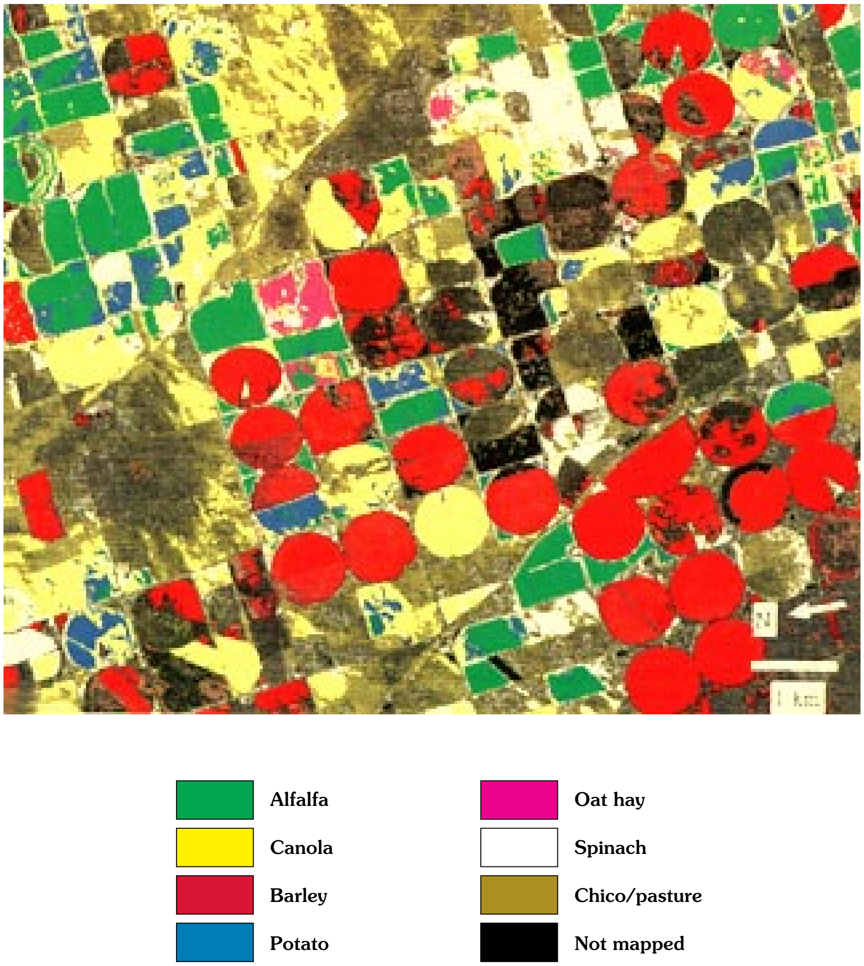
SAWATCH RANGE
SANGRE DE CRISTO MOUNTAINS
SAN LUIS VALLEY
SAN JUAN MOUNTAINS
CULEBRA RANGE
Bonanza
Kerber Creek
Saguache Creek
La Garita Creek
Great Sand Dunes
San Luis Lake
Del Norte
RIO GRANDE
Rock Creek
Alamosa
Monte Vista National Wildlife Refuge
Alamosa National Wildlife Refuge
Summitville
Terrace Reservoir
Alamosa River
Platoro
La Jara Creek
Conejos River
Antonito
Rio San Antonio
San Luis Hills
0
25 KILOMETERS
COLORADO
NEW MEXICO

IMAGING SPECTROSCOPY— A METHOD FOR MAPPING CROP DISTRIBUTION

Spectral imaging of minerals from aircraft was described previously, and this technique is also extremely useful in examining crop distribution. Just as minerals have unique spectral signatures, so do plants, trees, and soils. Laboratory spectral investigations of plants have shown that species can be identified using their visible and near-infrared spectra. The primary spectral features used for identification result from the presence of chlorophyll in plants, the organic material that gives plants a green color.

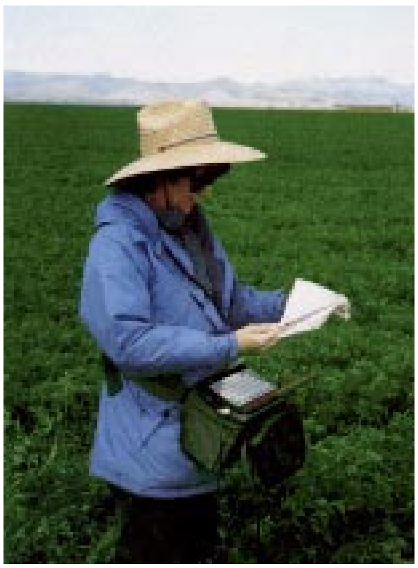
Details of the relation between chlorophyll in plants and their individual spectra are still poorly understood. Although the spectra of plants are sufficiently different to allow species identification, the spectra for an individual species can vary. Variations in plant spectra probably result from the amount of chlorophyll in the plant, a complex relation between the stages of the growing cycle and the health of the plant. The health of a plant can be affected by many factors including the amount of water it has available (too much or too little) or metal toxicity. Using AVIRIS data, maps were made of the distribution of crops, relative amounts of dry versus green vegetation, and relative health of specific crops in the lower San Luis Valley

Farmers in the San Luis Valley rely heavily on irrigation waters applied by center-pivot irrigation systems; thus, most farmed lands appear as circular areas in the remotely sensed data. Pasture land, fallow fields, and public lands not being used for agricultural purposes are usually not irrigated and do not appear as circular areas in the images. A number of crops, including alfalfa, canola, barley, hay, oats, potatoes, and spinach, were successfully mapped. Subtle but significant differences in the reflectance spectra of potatoes allowed the mapping of three different species. Pasture lands and areas of mixed green and dried vegetation were also mapped, providing a method to analyze crop distribution over large areas. Such methods are useful to land management agencies to inventory and assess land usage; however, more rigorous and thorough testing is required to determine the full capabilities and application of airborne imaging spectroscopy to agricultural problems.



AVIRIS image of the distribution of crops in the San Luis Valley, September 3, 1993. The circular patterns are the result of center-pivot sprinkling systems. Each of the colors corresponds to a specific crop. In areas that are black, no crops were mapped.

UPTAKE OF ELEMENTS BY ALFALFA AND BARLEY—ANOTHER WAY TO STUDY METAL DISPERSION



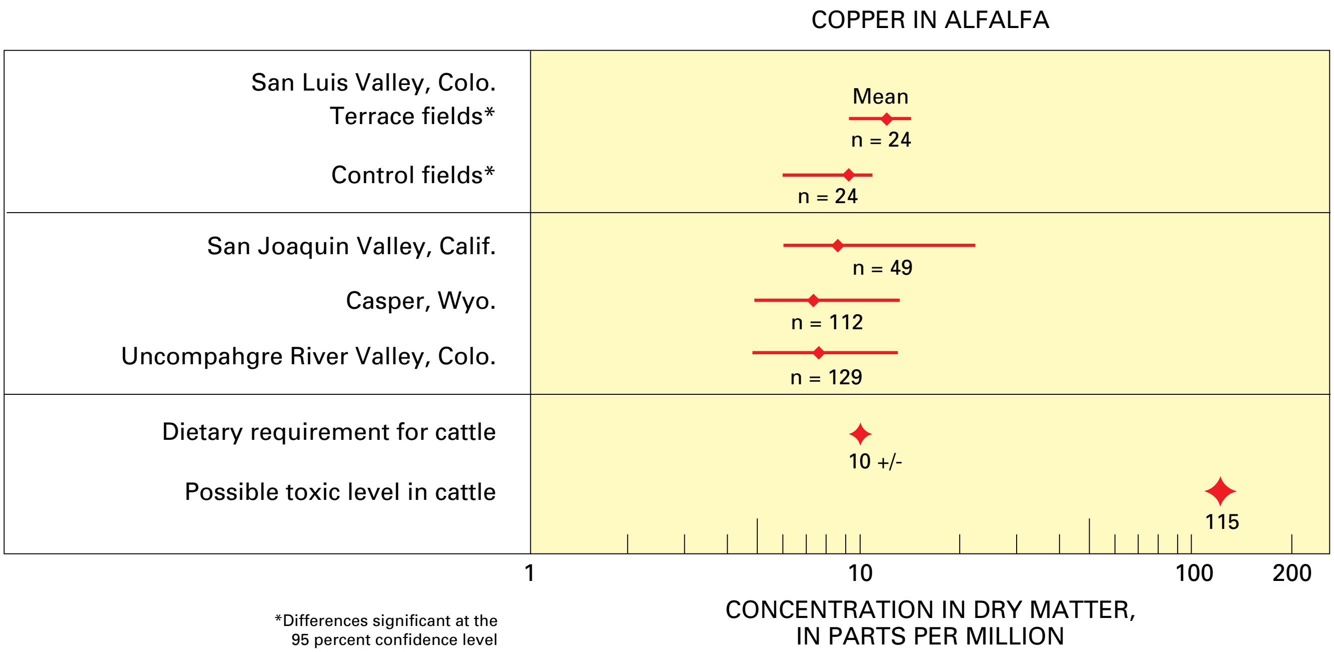
Terrace Reservoir receives water from the Summitville mine and surrounding areas and provides irrigation water to the southwestern part of the San Luis Valley. The composition of water and stream sediment from the Wightman Fork and the Alamosa River suggests that arsenic, chromium, copper, lead, nickel, manganese, and zinc are likely components of water being drawn from Terrace Reservoir. USGS scientists undertook two studies to determine the effects of this irrigation water on metal concentrations in alfalfa (a perennial crop) and barley (an annual crop) and their associated soils.

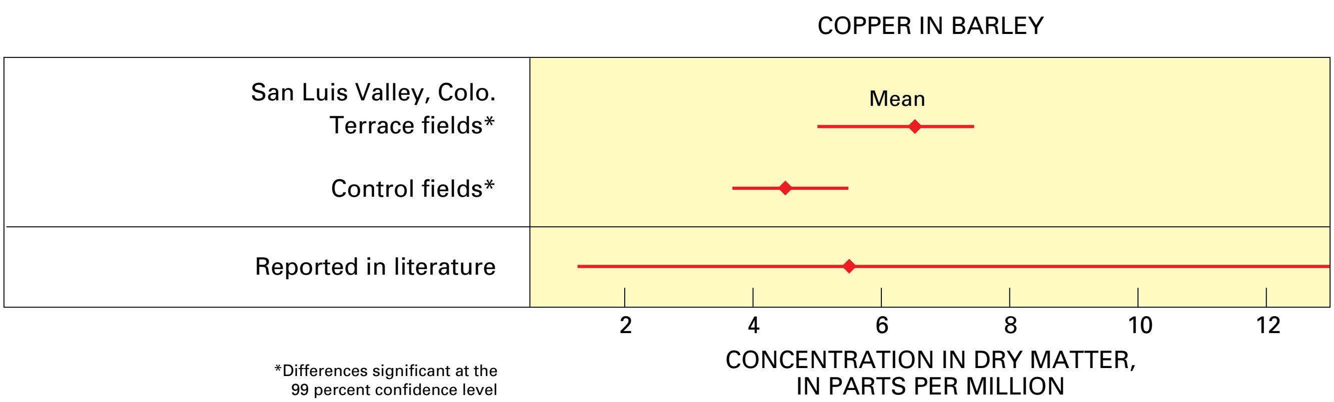
Two sources of irrigation water were examined and compared for several fields of similar soil types in center-pivot irrigated alfalfa and barley fields. The sources for the irrigation water were the Alamosa River (terrace fields) and the Rio Grande River and confined groundwater (control fields). The Alamosa River receives acidic metal-rich drainage, whereas the Rio Grande River and confined groundwater are uncontaminated.

A comparison of copper, manganese, and zinc concentrations from the two water sources indicates that water from the Alamosa River is more acidic (pH 5.6–6.8) than irrigation waters from the Rio Grande River or confined groundwater (pH 7.6–9.2) and contains much higher concentrations of these metals. Because the two sources of irrigation water have such different compositions, the question that needs to be addressed is are these differences also present in the crops and soils? Our studies suggest that the answer is no.

Comparison of the metal-concentration ranges for the soils irrigated by different water sources shows that copper, manganese, and zinc concentrations in the soils are generally similar. Comparison of these concentration ranges with those for soils collected throughout the Western United States indicates that the concentration ranges of the soils, regardless of the source of irrigation water, are within expected ranges.

Comparison of the copper concentrations in alfalfa and barley irrigated by different sources shows that copper concentrations of the crop in the fields irrigated with Alamosa River water are higher than those for fields irrigated with Rio Grande River water or confined groundwater. Concentration ranges are comparable, however, to those reported in other studies for different locations. Similar results were obtained for nickel.





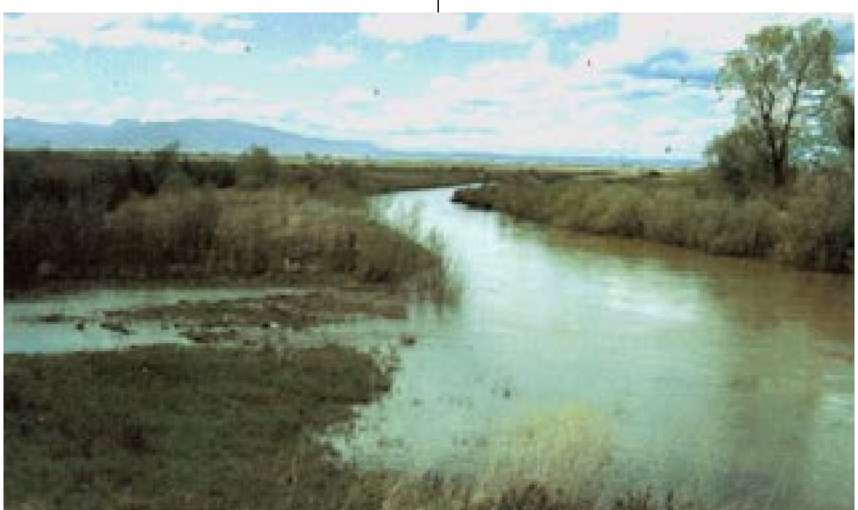
Copper concentrations in alfalfa and barley for the different irrigation sources in the study area compared to copper concentrations in alfalfa and barley determined during other studies reported in the literature. For both alfalfa and barley, the copper concentrations of the crops in the fields irrigated with Alamosa River water (terrace fields) are greater than those for fields irrigated with Rio Grande River water or confined groundwater (control fields); however, the ranges of concentrations are comparable to those reported in the literature for other locations in the Western United States.

If nutritional requirements for cattle are considered, alfalfa irrigated with both sources of water meets published nutritive requirements and contains amounts of metals far below concentrations reported to be toxic to cattle. Interestingly, the higher copper concentrations in alfalfa grown in fields irrigated with Alamosa River water are commonly in the sufficient range of nutrient status, whereas alfalfa grown in fields irrigated with Rio Grande River water or confined groundwater extends into the low range of nutrient status. Similar results were obtained for manganese and zinc.

Thus, although concentrations of many metals in irrigation water affected by the Summitville mine are higher than in other local irrigation-water sources, these metal-rich irrigation waters have only a slight effect on the bulk soil composition and a minimal effect on the metal content of the crops. None of the metal values in alfalfa is near toxic levels, and some metal levels can be considered somewhat beneficial to the nutritional value for alfalfa.

BIOGEOCHEMICAL EXAMINATION OF THE ALAMOSA NATIONAL WILDLIFE REFUGE

To examine the nature and extent of the effects of acid drainage on the biogeochemistry of wetlands in the San Luis Valley, the USGS initiated a study of the Alamosa National Wildlife Refuge (shown below). Water and stream sediments were collected in June 1993 from the Wightman Fork and from 10 sites along the Alamosa River. In addition, water, sediment cores, and aquatic plants (*Polegonum amphibia*) were collected from nine wetlands just west of and within the Alamosa National Wildlife Refuge. The sources of water entering the wetlands include the Alamosa River, or a mixture of La Jara Creek and Alamosa River water, and the Rio Grande River.



Data for sediment and water samples collected in the Alamosa River suggest that both the Summitville mine and the unmined mineralized areas are sources of copper. Using data collected upstream from the confluence of the Wightman Fork and the Alamosa River as baseline level, the study suggests that dissolved copper was introduced into the Alamosa River by the Wightman Fork waters during June 1993. The concentration of copper decreases as the waters flow toward and along the valley floor. There is some indication that the level of copper remains above the baseline value in the wildlife refuge.

Analysis of sediments collected above and below the confluence of the Wightman Fork and the Alamosa River suggests that copper levels are influenced by drainage from the Wightman Fork and the tributaries draining the Jasper area. The presence of amorphous, iron-enriched particles in the river, the downstream dilution of dissolved metal concentrations, and the downstream enrichment of metals in sediment are consistent with the deposition of toxic elements from the water, their transport in the solid phase, and settling out as the water velocity decreases.

The waters in the wetlands have high pH values, in contrast to the low pH values for acid drainage, and generally contain low concentrations of heavy metals. A comparison of sediment samples from the Alamosa River and Rio Grande River shows, however, that the accumulation rate for cobalt, chromium, copper, nickel, vanadium, and zinc is greater in that part of the wetland that receives water from the Alamosa River. Other elements, such as arsenic, cesium and lead, show no significant enrichments that can be attributed to differences in the source of water and sediment. Studies of aquatic plants in the wetlands show that plants receiving Alamosa River water contain more copper and zinc than plants that receive water from other sources. Thus, certain elements associated with acid drainage from both mined and unmined areas are being introduced into the wetlands. Further, the chemical composition of the wetlands near and within the Alamosa National Wildlife Refuge is dependent in large part on the source of the water.

SUMMARY

Results of USGS research at the Summitville mine site in Colorado underscore the crucial need for sound scientific information in predicting, assessing, and remediating the environmental effects of mining. Although final scientific judgments about Summitville and its downstream environmental effects await the outcome of all of the research, some preliminary conclusions can be drawn.

- Extreme acid-rock drainage is the dominant long-term environmental concern at the Summitville mine and could have been predicted given the geologic characteristics of the deposit. Extensive remedial efforts are required to isolate both unweathered sulfides and soluble metal salts in the open-pit area and mine-waste piles from weathering and dissolution.
- It is likely that natural contamination adversely affected water quality and fish habitat in the Alamosa River long before mining and will continue to have adverse effects even when acid drainage from Summitville is remediated. Thus, reasonable natural conditions for the Alamosa River basin must be established in order to set realistic remediation standards for the Summitville site.
- Results of studies as of late 1993 indicate that mining at Summitville has had no discernible short-term adverse effects on barley or alfalfa crops irrigated with Alamosa River water. Remediation of the site will help to ensure that no adverse effects occur over the longer term.

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