

Questa Baseline and Pre-Mining Ground-Water Quality Investigation. 19. Leaching Characteristics of Compositated Materials from Mine Waste-Rock Piles and Naturally Altered Areas near Questa, New Mexico



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Cover: Photograph of the upper bench of the Sugar Shack South waste-rock pile at the Questa Mine, New Mexico. Photograph taken by Paul Briggs.

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By Kathleen S. Smith, Philip L. Hageman, Paul H. Briggs, Stephen J. Sutley,
R. Blaine McCleskey, K. Eric Livo, Philip L. Verplanck, Monique G. Adams,
and Pamela A. Gemery-Hill

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**U.S. Department of the Interior
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Conversion Factors

Multiply	By	To obtain
Length		
centimeter (cm)	0.3937	inch
millimeter (mm)	0.03937	inch
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
Volume		
liter (L)	33.82	ounce, fluid (fl. oz)
liter (L)	2.113	pint (pt)
liter (L)	1.057	quart (qt)
liter (L)	0.2642	gallon (gal)
liter (L)	61.02	cubic inch (in ³)
milliliter (mL)	0.0338	ounce, fluid (fl. oz)
Flow rate		
cubic meter per second (m ³ /s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m ³ /s)	35.31	cubic foot per second (ft ³ /s)
cubic meter per second (m ³ /s)	22.83	million gallons per day (Mgal/d)
Mass		
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)

Multiply	By	To obtain
Length		
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
Volume		
ounce, fluid (fl. oz)	0.02957	liter (L)
pint (pt)	0.4732	liter (L)
quart (qt)	0.9464	liter (L)
gallon (gal)	3.785	liter (L)
cubic inch (in ³)	0.01639	liter (L)
Flow rate		
acre-foot per day (acre-ft/d)	0.01427	cubic meter per second (m ³ /s)
cubic foot per second (ft ³ /s)	0.02832	cubic meter per second (m ³ /s)
million gallons per day (Mgal/d)	0.04381	cubic meter per second (m ³ /s)
Mass		
ounce, avoirdupois (oz)	28.35	gram (g)
pound, avoirdupois (lb)	0.4536	kilogram (kg)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$^{\circ}\text{F}=(1.8\times^{\circ}\text{C})+32$$

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

$$^{\circ}\text{C}=(^{\circ}\text{F}-32)/1.8$$

Specific conductance is given in microsiemens per centimeter at 25 degrees Celsius (μS/cm at 25°C).

Concentrations of chemical constituents in water are given either in milligrams per liter (mg/L) or micrograms per liter (μg/L).

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Abstract

The goal of this study is to compare and contrast the leachability of metals and the acidity from individual mine waste-rock piles and natural erosional scars in the study area near Questa, New Mexico. Surficial multi-increment (composite) samples less than 2 millimeters in diameter from five waste-rock piles, nine erosional-scar areas, a less-altered site, and a tailings slurry-pipe sample were analyzed for bulk chemistry and mineralogy and subjected to two back-to-back leaching procedures. The first leaching procedure, the U.S. Geological Survey Field Leach Test (FLT), is a short-duration leach (5-minute shaking and 10-minute settling) and is intended to leach readily soluble materials. The FLT was immediately followed by an 18-hour, end-over-end rotation leaching procedure. Comparison of results from the back-to-back leaching procedures can provide information about reactions that may take place upon migration of leachates through changing geochemical conditions (for example, pH changes), both within the waste-rock and scar materials and away from the source materials.

For the scar leachates, the concentrations of leachable metals varied substantially between the scar areas sampled. The scar leachates have low pH (pH 3.2–4.1). Under these low-pH conditions, cationic metals are solubilized and mobile, but anionic species, such as molybdenum, are less soluble and less mobile. Generally, metal concentrations in the waste-rock leachates did not exceed the upper range of those metal concentrations in the erosional-scar leachates. One exception is molybdenum, which is notably higher in the waste-rock leachates compared with the scar leachates. Most of the waste-rock leachates were at least mildly acidic (pH 3.0–6.2). The pH values in the waste-rock leachates span a large pH range that includes some pH-dependent solubility and metal-attenuation reactions. An increase in pH with leaching time and agitation indicates that there is pH-buffering capacity in some of the waste-rock piles. As pH increased in the waste-pile leachates, concentrations of several metals decreased with increasing

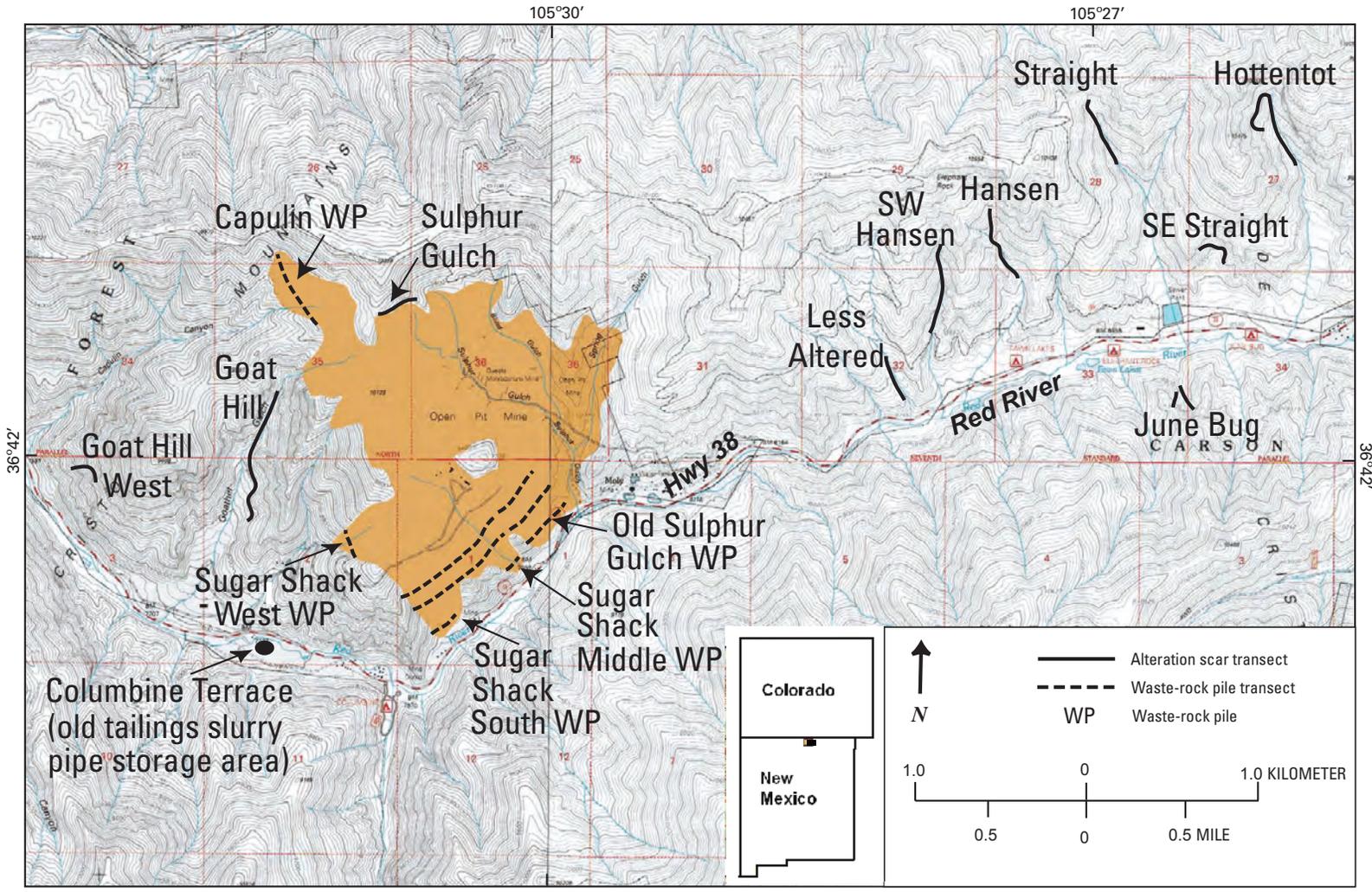
time and agitation. Similar pH-dependent reactions may take place upon migration of the leachates in the waste-rock piles.

Bulk chemistry, mineralogy, and leachate sulfur-isotope data indicate that the Capulin and Sugar Shack West waste-rock piles are compositionally different from the younger Sugar Shack South, Sugar Shack Middle, and Old Sulphur Gulch piles. The Capulin and Sugar Shack West piles have the lowest-pH leachates (pH 3.0–4.1) of the waste-pile samples, and the source material for the Capulin and Sugar Shack West piles appears to be similar to the source material for the erosional-scar areas. Calcite dissolution, in addition to gypsum dissolution, appears to produce the calcium and sulfate concentrations in leachates from the Sugar Shack South, Sugar Shack Middle, and Old Sulphur Gulch piles.

Introduction

In April 2001, the U.S. Geological Survey (USGS) and the New Mexico Environment Department began a cooperative study to infer the pre-mining ground-water chemistry at the Molycorp, Inc., Questa molybdenum mine site in the Red River Valley of New Mexico (fig. 1; Nordstrom, 2005; in press; Nordstrom and others, 2002, 2003). The Molycorp mine, which extracts molybdenite (MoS_2) ore, has been operating intermittently since the 1920s and has been a large-scale mining operation since an open pit was developed in 1965. Possible contaminants of concern from the mine include arsenic, cadmium, chromium, cobalt, copper, lead, manganese, silver, and zinc (U.S. Environmental Protection Agency, 2000).

Steep, barren cliffs of hydrothermally altered rocks (termed erosional scars) weather and produce areas of mass wasting (fig. 2) in the northern portion of the Red River Valley between the towns of Questa and Red River, New Mexico. These natural erosional scars result from the oxidation of pyrite-rich mineralized rock. Regional hydrothermal mineralization and alteration formed both the mineral deposits at the Molycorp mine and the scars in the Red River Valley.



Base from U.S. Geological Survey Red River and Questa quadrangles, 1:24,000 (1995).

Figure 1. Map of the study area near Questa, New Mexico. Dashed lines show sampling transects for waste-rock piles, and solid lines show sampling transects for the natural scar areas. (Map prepared by Philip Verplanck.)



Figure 2. Photograph of Southwest Hansen Creek (also known as Little Hansen Creek) scar showing the high relief and barren nature of the natural erosional scars, near Questa, New Mexico. (Photograph taken by Paul Briggs.)

Previous studies by Robertson GeoConsultants, Inc., have examined the characteristics of the scar areas (Robertson GeoConsultants, Inc., 2000a, 2001a; Shaw and others, 2003) and the waste-rock piles (PetraScience Consultants, 2001; Robertson GeoConsultants, Inc., 2000b, 2000c; Shaw and others, 2002; Wels and others, 2002). A previous USGS study reported on the chemistry and mineralogy of samples discussed in this report (Briggs and others, 2003). Other USGS investigations conducted in the study area report on detailed mineralogy and solids chemistry of unmined but altered rock from surface samples and drill cuttings (Plumlee and others, 2005), regional mineralogy (Livo and Clark, 2002a, 2002b; Livo and Knepper, 2004), geology (Ludington and others, 2004), chemical weathering (Plumlee and others, 2006), and water composition of the Red River (Ball and others, 2005; Kimball and others, 2006; Maest and others, 2004; McCleskey and others, 2003; Verplanck and others, 2006).

This report addresses the leaching characteristics of surficial samples of composited mine waste-rock material

and of naturally altered areas. Leaching information can be used to evaluate potential metal and acid release to receiving streams and shallow ground water. The goals of this study are to compare and contrast leachate data from individual mine waste-rock piles and natural erosional scars in the study area, and to compare the concentration ranges of the solubilized metals from the different sources. These data lend insight into the chemical differences of waste-rock piles and erosional scars in the Questa area.

Physical Setting, General Geology and Hydrology, and Mining History

Geographic and Physiographic Features

The study area is in Taos County in the Taos Range of the Sangre de Cristo Mountains of north-central New Mexico (fig. 1). The Red River drainage basin is a tributary to the Rio Grande within the Carson National Forest. The area is a rugged and altered terrain with steep slopes and V-shaped valleys (fig. 1). The study reach of the Red River is in the Red River Valley between the Questa Ranger Station at 2,280-m elevation at the west end and the town of Red River at 2,646-m elevation at the east end. The canyon walls of the Red River Valley climb rapidly from 2,400 m to more than 3,000 m at the ridge crest on both the north and south sides of the river. Some peaks reach nearly 3,500 m. The 600-m difference in elevation between the Red River and the adjacent ridge crest can occur over a horizontal distance of less than 2,000 m.

The Molycorp, Inc., Questa molybdenum mine, referred to as the mine site, is located on the north side of State Highway No. 38 and the Red River, 13 km east of the mountain front and mouth of the Red River canyon. The mine site is approximately 16 km² and encompasses three main tributary valleys to the Red River: Capulin Canyon, Goat Hill Gulch, and Sulphur Gulch, from west to east, respectively (fig. 1).

Mining activities produced extensive underground workings and an open pit of approximately 0.65 km² near or in Sulphur Gulch. Waste-rock piles cover steep slopes on the north side of the Red River between Capulin Canyon and Spring Gulch (a tributary valley of Sulphur Gulch). Hydrothermally altered and extensively fractured and faulted areas of bedrock are present in Capulin, Goat Hill, Sulphur, Hansen, Straight, June Bug, and Hottentot drainages (fig. 1). The latter four drainages are examples of unmined drainages. Weathering of extensively altered rock along fracture networks and fault zones has resulted in steep, highly erosive, sparsely vegetated “alteration scars” that are clearly visible from the ground and in aerial photographs (Meyer and Leonardson, 1990). Where there has been no mining, these scar areas also are important natural sources of trace-metal and acid loading to surface and ground waters.

Climate and Vegetation

The Red River Valley lies within a semiarid desert that receives precipitation throughout the year and sustains moderate biodiversity. Between 1915 and 2002, the average annual temperature was 4°C, the average precipitation and snowfall were 52 cm and 370 cm, respectively, and the daily temperatures generally fluctuated by 18°C throughout the year (Western Regional Climate Center, written commun., 2005).

Climate and vegetation vary greatly within short distances because of differences in topography, weather, bedrock, and sediment composition. Orographic effects of mountainous topography lead to precipitation on the windward slopes and localized storms within tributary valleys. Major precipitation events include summer thunderstorms and winter-spring snowstorms. Thunderstorms lead to mass wasting in hydrothermally altered scar areas, producing debris flows that potentially affect vegetation, alluvial aquifers, and the Red River. Winter snowpack contributes to ground-water recharge through snowmelt infiltration and runoff.

Prevalent vegetation in the Red River Valley is representative of the following altitude zones: piñon-juniper woodland (1,800–2,300 m), mixed conifer woodland (2,300–2,740 m), and spruce-fir woodland (2,740–3,660 m; Knight, 1990). Willows, cottonwoods, shrubs, perennial grasses, and flowering vegetation are common near the banks of the Red River. Extending from the river are widely spaced piñon pines and junipers. Gains in altitude give rise to an abundance of ponderosa pines and limber pines, whereas Douglas fir and white fir can grow at higher altitudes. This typical mountain community, although diverse, is dominated by ponderosa pines (Larry Gough, U.S. Geological Survey, oral commun., 2003).

General Geology

The geochemical interaction of water with soil, colluvium, alluvium, and fractured bedrock produces the composition of surface and ground waters that are the overall focus of the baseline and pre-mining ground-water quality investigation. Hence, the geology is a fundamental component to understanding the hydrology and ground-water chemistry. This section briefly summarizes the general geologic framework from several studies (Lipman, 1981; Meyer and Leonardson, 1990, 1997; Rehrig, 1969; Schilling, 1956), in addition to observations made by the USGS scientists currently working at the site.

The Taos Range is composed of Precambrian metamorphic rocks and granitic intrusive rocks overlain and intruded by Tertiary volcanic and plutonic rocks (Lipman and Reed, 1989). The volcanic rocks are primarily intermediate to felsic composition (andesites to rhyolites) and are intruded by late Oligocene and early Miocene quartz monzonites and granites that provided the source of the hydrothermal fluids and molybdenite mineralization. The hydrothermally altered volcanics commonly contain pyrite mineralization (generally 1–3 percent). The Red River Valley is located along the southern edge

of the Questa volcanic caldera and contains complex structural features and extensive hydrothermal alteration associated with the evolution of the Rio Grande rift. The mineral deposits in the Red River Valley are considered Climax-type deposits that are associated with silica- and fluorine-rich rhyolite porphyry and granitic intrusives. The three principal alteration zones include highly altered quartz-sericite-pyrite (QSP), less-altered argillic (dominantly kaolinite) zones, and mildly altered propylitic zones (containing calcite mineralization). QSP alteration, as the name implies, produces a mixture of quartz, pyrite (up to 10 percent), and fine-grained mica (sericite) or illite. Chlorite, epidote, albite, and calcite typically are present in the propylitic assemblages. Ore deposits contain quartz, molybdenite, pyrite, fluorite, calcite, manganiferous calcite, dolomite, and rhodochrosite. Lesser amounts of galena, sphalerite, chalcocopyrite, magnetite, and hematite also are present. The hydrothermal alteration related to mineralization overprints an older, regional propylitic alteration. In these areas, rocks can contain a mixture of quartz, pyrite, and illite clays replacing feldspars, chlorite, carbonates, and epidote. Abundant minerals in waste rock produced by mining activities include chlorite, gypsum, illite, illite-smectite, jarosite, kaolinite, and muscovite (Gale and Thompson, 2001).

Andesite volcanic and volcanoclastic rocks are present in most scar-area bedrock outcrops and are the dominant bedrock units in the Straight Creek, Southeast Straight Creek, Sulphur Gulch, and Southwest Hansen scars (Ludington and others, 2004, and fig. 1). Amalia Tuff, a mildly alkaline, rhyolitic tuff, is the dominant rock type in the Goat Hill and Hansen scars, and quartz latite porphyry is the main rock type in the June Bug and Hottentot (southeast side) scars (fig. 1). Rhyolite porphyry is the main rock type in the Hottentot scar, and quartz latite and rhyolite porphyries form the hill slopes of many scars. Rhyolite porphyry and tuff do not seem to have been substantially affected by propylitization. Advanced argillic alteration was identified in the Hansen and Hottentot scars and in areas southwest of the Molycorp open pit. Propylitized andesite bedrock is present in several drainages that typically do not contain alteration scars.

After the Amalia Tuff erupted and the Rio Grande rift began to form 26 million years ago, the landscape of the study area consisted of a broad, low-relief plateau (Peter Lipman, U.S. Geological Survey, written commun., 2005). Rifting has caused as much as 7 km of structural relief across the Sangre de Cristo fault system — the eastern structural boundary of the rift and the western boundary of the Sangre de Cristo mountain block (Grauch and Keller, 2004; Kluth and Schafteenaar, 1994). Tectonically driven uplift caused the Red River to incise into the Taos Range, resulting in the development of the present rugged terrain (Kirk Vincent, U.S. Geological Survey, written commun., 2005). However, more than a million years ago the Red River was essentially the headwater of the Rio Grande, and it flowed near the level of the top of the sediments within the rift basin (Wells and others, 1987). About 700 to 600 thousand years ago the San Luis Basin was captured by the Rio Grande, which strikingly increased discharges,

increased incision in the Rio Grande and tributary watersheds, and relegated the Red River to the status of one of those tributaries (Wells and others, 1987). Although thin Pleistocene alpine glaciers formed in the highest peaks of the Sangre de Cristo Mountains, they likely had little influence on the form of the Red River Valley.

During the late Holocene, forested hillslopes eroded at about 0.04 mm/yr as compared to the then-exposed alteration scars, which eroded at about 3.0 mm/yr (Kirk Vincent, U.S. Geological Survey, written commun., 2005). This extremely rapid erosion rate caused tributary watersheds containing alteration scars to deliver more sediment to the Red River than it could transport away, thus developing large debris fans to interfinger with alluvial sediments within the valley (Kirk Vincent, U.S. Geological Survey, written commun., 2005). These hydrothermally and structurally controlled facies relations have resulted in significant heterogeneities within the generally high permeability Red River Valley alluvial aquifer because the fan deposits have several orders of magnitude lower permeability than the alluvial deposits.

Tectonic deformation, in addition to and accompanying igneous and exhumation processes from Precambrian through Holocene times, has produced a highly complex array of folds, fault zones, fractures, and veins. Since the inception of the Questa caldera in the Oligocene, the region around the Red River Valley has been in a tensional stress regime, which has ultimately produced the ancient and modern Rio Grande rift previously discussed (Meyer and Foland, 1991). Generally north-northwest- to north-northeast-striking extensional fault zones that have been progressively reactivated during the coupled development of the caldera, ore mineral system, and the eastern rift flank have accommodated approximately 200-percent extensional strain focused in the caldera (Meyer and Foland, 1991). These fault zones show a wide variety of internal deformation and structures, degree of mineralization, and dip. Numerous fracture networks, joints, and veins pervasively penetrate the entire study area. Collectively, these brittle structures form the permeability structure in otherwise generally low permeability crystalline rock in which the modern geochemical and ground-water-flow system exists.

Bedrock at the surface and buried under alluvial, colluvial, and anthropogenic deposits shows a variable and complex zone of weathering. Samples collected from a bedrock weathering profile in the Straight Creek scar were studied in detail to characterize the mineralogic variations in a weathered profile (Ludington and others, 2004). Relatively unweathered bedrock exposed in the creek bottom is propylitized andesite with a QSP overprint. Depending on location within the weathering profile, altered rocks contain variable amounts of quartz, illite, chlorite, and plagioclase feldspar, with smaller amounts of pyrite, gypsum, rutile, jarosite, and goethite (Livo and Clark, 2002b; Ludington and others, 2004). Calcite, goethite, and sericite are widely distributed in the Red River Valley rocks and soils, as revealed by Airborne Visible/InfraRed Imaging Spectrometry (AVIRIS; Livo and Clark, 2002b). Calcite is an important mineral in the Red River Valley because its

dissolution effectively neutralizes the acid inflows so that pH values in the Red River tend to be alkaline (pH 7–8). Gypsum is common throughout the Red River Valley and forms as a secondary product of acid-sulfate weathering when pyrite oxidizes and reacts with calcite. Because gypsum is soluble in water, calcium and sulfate are the major ions for most surface and ground waters in the Red River Valley.

The major minerals in rock samples collected during mineral exploration and mining are biotite, calcite, chalcocopyrite, fluorite, galena, molybdenite, pyrite, quartz, rhodochrosite, and sphalerite. Mining activities produced roughly 328 million tons of rock overburden in Capulin Canyon and adjacent gulches along the north slope of the Red River (URS, 2001). The abundant minerals in waste-rock samples include chlorite, gypsum, illite, illite-smectite, jarosite, kaolinite, and muscovite (Gale and Thompson, 2001).

Mining History

Before 1916, prospectors discovered outcrops of rich, yellow, weathered rock that looked like sulfur (hence the name, Sulphur Gulch) and a greasy mineral that looked like graphite (fig. 1). The graphitic mineral was identified as molybdenite (MoS_2) in 1916 and the yellow mineral was ferromolybdate, the oxidized product derived from the weathering of molybdenite (Schilling, 1956). By 1920 the Molybdenum Corporation of America had acquired the property to mine the deposit, and the company subsequently shortened its name to Molycorp, Inc. A mill and flotation plant were set up by 1923 for production and small-scale underground mining of high-grade veins (averaging 4 percent with a maximum of 35 percent), which continued until 1958. During the 1950s, exploration had identified a large, low-grade deposit (about 0.3 percent) below the high-grade deposit, and the decision was made to extract this ore by open-pit methods (Carpenter, 1968). Extraction of open-pit ore began in 1965, and tailings were transported by a 15-km-long pipeline to a tailings facility in the Rio Grande Valley just west of Questa. Peak production occurred in 1976 with 11.5 million pounds per year. In 1977, Molycorp, Inc., became a wholly owned subsidiary of Union Oil Company of California.

Open-pit mining ceased in 1983 and underground mining restarted. Waste rock was no longer dumped onto piles at the mine site, but the amount of tailings increased. Low market values for molybdenum have periodically caused the mine to shut down (1986–89 and 1992–95). Active mining continues at Molycorp's Questa mine in response to market demand. Further history and related information on the Molycorp Questa mine is available from Molycorp, Inc., (www.molycorp.com) and from the U.S. Environmental Protection Agency (USEPA) (U.S. Environmental Protection Agency, 2006).

Waste-Rock Pile History

Open-pit mining operations at the Molycorp Questa mine occurred between 1965 and 1983. During the open-pit mining

process, waste rock was placed in various piles at the mine site. The Sugar Shack West and Capulin waste-rock piles are among the oldest piles constructed during open-pit mining. Three roadside waste-rock piles (Old Sulphur Gulch, Sugar Shack South, and Sugar Shack Middle) were constructed using a “wrap around” method. In the early/middle stages of open-pit mining, waste rock was dumped from the higher points of these rock piles. As the open pit developed, benches were wrapped around the front of the existing piles. No additional material has been placed on the roadside piles since 1985 (Bruce Walker, Molycorp, written commun., 2005; Robertson GeoConsultants, Inc., 2000d).

General Hydrology

Surface Water

The Red River originates at an altitude of approximately 3,658 m near Wheeler Peak, the highest peak in New Mexico (4,011 m), and flows roughly 55 km to its confluence with the Rio Grande at an altitude of 2,012 m. Total basin drainage area is 492 km², and the drainage area upstream from the Questa Ranger Station gaging station (at the mouth of the Red River Canyon) is 293 km². Peak streamflow typically occurs from late May to mid-June, with snowmelt-related flows beginning in late March and increasing through mid-April. Summer thunderstorms are prevalent in July and August. Between 1930 and 2001, the mean annual discharge of the Red River at the Questa Ranger Station gage ranged from 0.36 to 2.92 m³/s, and the average daily discharge ranged from 0.07 to 21.24 m³/s with an average of 1.33 m³/s (U.S. Geological Survey, 2004). The main drainages in the vicinity of the mine site are Capulin Canyon, Goat Hill Gulch, and Sulphur Gulch on the north side of the Red River.

Springs and shallow alluvial ground-water discharge into the Red River, rendering it a gaining stream over much of its length (Smolka and Tague, 1989). Between the town of Red River and the gaging station near Questa, there are many ephemeral seeps and springs along the banks of the Red River and also intermittent seeps and springs in tributary drainages on the north side of the river (South Pass Resources, Inc., 1995; Steffen, Robertson, and Kirsten, 1995; Robertson GeoConsultants, 2001b). Aluminum hydroxide often precipitates from springs downgradient from scar and mined areas on the north side of the Red River, affecting the color and turbidity of the river (Vail Engineering, Inc., 1989).

Ground Water and Aqueous Geochemistry

Aquifer units in the Red River Valley are highly varied. Waste-rock piles and scars with associated debris fans are geochemically reactive and have high porosity and relatively high permeability. Alluvial aquifers are localized and have variable compositions. Hillslope soils are thin and composed of materials eroded from adjacent upgradient slopes. Debris fans are composed of sediments rapidly shed from their respective

watersheds. Where the tributary watersheds contain erosional scars, the debris fans are large and active and contain both coarse- and fine-grained, largely unsorted, clay-rich debris-flow sediments, making them heterogeneities in the alluvium as discussed previously.

The chemistry of these sediments reflects the chemistry of their source terrains. The rapidly eroding and altered erosion scars have source materials that can generate low-pH, trace-metal-rich ground waters. Sediments deposited by the Red River, in contrast, generally consist of well-washed, rounded sands, gravels, and cobbles and are composed of a mix of lithologies present in the entire Red River Valley, including carbonates from the uppermost reaches. The largest debris fans caused the Red River alluvium to aggrade behind the fans during the Quaternary. Thus, ground water flowing in the shallow alluvial aquifer passes alternately through Red River alluvium and debris fans and may emerge when a relatively low permeability fan is encountered. Both the Red River alluvium and the debris fans act as a complex aquifer unit that is less than several hundred meters wide and less than 100 m thick.

Alluvial ground water is a calcium-sulfate water type, with magnesium commonly the second most abundant cation. Ground water downgradient from the waste-rock piles and scars has acidic pH values and elevated metal concentrations compared to ground water upgradient from these altered areas.

The bedrock aquifer is the largest aquifer in the study area but probably contains only relatively small amounts of ground water below the weathered zone because of its inferred low porosity and low permeability, largely controlled by fracture networks. Bedrock ground waters are also calcium-sulfate type but generally of neutral pH. Most wells developed in the Red River Valley were installed to monitor water quality downgradient from mining operations (waste-rock dumps and tailings piles), scar areas, or both. Wells installed in the Straight Creek drainage (fig. 1) during the USGS study were developed to measure water levels and collect water-chemistry data for a range of environments in the Red River Valley. The aim of this work was to identify and interpret water/rock interactions under non-mining baseline conditions as a reference to infer pre-mining water/rock interactions for the mine site.

Hydrothermal alteration produced substantial changes in mineralogy over relatively short distances, which is a common feature of hydrothermally altered terrains. Hence, both the mineralogy and the resultant water chemistry can change substantially on a small spatial scale. Such hydrogeochemical environments are described as highly heterogeneous. This heterogeneous character makes the estimation of pre-mining ground-water chemistry for an area the size of the mine site a highly variable function of changing lithology at the mine site.

Methods

Sampling Strategy

The scar areas and waste-rock piles pose a formidable sampling challenge because of their size, steepness, and heterogeneity. The sampling strategy used in this study was modified from Smith and others (2000). Multi-increment (composite) samples of surficial material were obtained by collecting multiple increments (that is, subsamples) along transects of the scars and waste-rock piles. Subsamples were collected along transects because complete sampling of scars and waste-rock piles posed safety hazards caused by the steep, “ball bearing” nature of the material covering their surfaces.

Multi-increment sampling was used to focus on the average geochemical behavior of a given scar or waste-rock pile rather than the amount of geochemical variation within it. Use of this multi-increment sampling approach allows differences between waste-rock piles or scars to be addressed and makes it possible to identify potential sources of contaminants. One 30-increment sample collected using this sampling strategy contains as much information, relative to average value, as 30 individual grab samples (Smith and others, 2000).

The scars and rock piles likely generate a substantial amount of surface runoff because they are steep and devoid of vegetation. As this runoff would be in contact with the surficial material of the waste-rock piles and scar areas, only the surficial material was sampled in this study. The surficial material is geochemically dynamic in that it is in contact with the atmosphere and is exposed to seasonal variations in temperature and precipitation. During dry cycles, secondary and tertiary minerals may precipitate in near-surface areas; during wet cycles, these precipitated minerals may be rinsed away. It is likely that runoff from the scar areas ultimately infiltrates the alluvial fans and shallow ground-water systems downgradient from the scar areas.

The target population for sampling was defined as the surficial (less than 15-cm depth) material along one or more transects of a given scar or waste-rock pile, dry-sieved to less than 2 mm. The subsamples were randomly collected at equal, predetermined distances along the transects and consisted of a minimum of 30 increments collected with a stainless steel trowel and plastic bucket. In the scar areas, subsamples of approximately 100 grams were collected at stream level, alternating between right and left banks when possible, and placed into a 5-gallon plastic bucket. At the waste-rock piles, subsamples of approximately 100 grams were collected along transects and placed into a 5-gallon plastic bucket. Each subsample was taken randomly every 20 paces along a transect, and particles greater than pebble size were not collected. The multi-increment samples were brought back to the Denver USGS laboratories, air-dried, mixed, and dry-sieved through a stainless steel screen to less than 2 mm. Each final <2-mm multi-increment sample weighed at least 1 kg.

Scar samples were collected from the following nine drainages: Goat Hill, Goat Hill West, Hansen Creek, Hottentot Creek, June Bug, Straight Creek, Sulphur Gulch, Southeast Straight Creek, and Southwest Hansen Creek (also known as Little Hansen Creek, figs. 1–3; see Ludington and others, 2004). The Goat Hill West scar was sampled during the same sampling trip as the Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South waste-rock piles. In addition to the scar samples, a sample was collected in a less-altered area in the unnamed drainage west of Southwest Hansen Creek. Mine waste-rock samples were collected from the following five piles: Capulin, Old Sulphur Gulch, Sugar Shack Middle, Sugar Shack South, and Sugar Shack West (fig. 1, fig. 4). These piles represent about three-fourths of the total waste rock produced at the Questa mine site.

The waste-rock multi-increment samples were collected on two different collection trips, under different weather conditions and by different samplers, because of inclement weather during the first sampling trip. The samples collected from Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South were collected during wet conditions from three transects, including the base and two benches, for each pile. The three-transect multi-increment samples for each pile were combined to make one composite for the entire pile. The multi-increment samples collected from Capulin and Sugar Shack West were collected during dry conditions from one transect. For Capulin, the transect was 3 to 6 meters below the top of the pile, along the length of the pile. For Sugar Shack West the transect was along a bench approximately 12 meters above the base of the pile. It is not known what effects sampling under wet compared to dry conditions have on the leachate data, but all samples were air dried before any laboratory work. In addition to the waste-rock pile samples, a tailings sample was collected from an old tailings slurry pipe (fig. 1) on Columbine Terrace near the Red River. This grab sample was collected from the end of the slurry pipe located along the Red River. The slurry pipe was used to transport tailings from the milling facility to the tailings ponds.

In designing the sampling strategy, sampling errors were addressed in several ways. The fundamental sampling error (FSE) results from particles having different compositions and generally is the largest single source of sampling error. Important factors influencing the FSE include degree of heterogeneity, sample mass, and particle size. The scar areas and waste-rock piles have a large degree of heterogeneity (including compositional, spatial, and particle size). The FSE was reduced in our sampling strategy by decreasing the particle size. The <2-mm particle size was chosen as the cutoff, which was found in a previous study (Smith and others, 2000) to encompass the most reactive material in mine-waste piles. Used in combination with leaching studies, the <2-mm size fraction may tend to slightly overestimate the leachability of the material as a whole, but this size-fraction cutoff does not appear to miss any leachable phases. Therefore, the <2-mm size fraction seems a good choice to reduce the FSE. The



Figure 3. Photograph of Hottentot Creek illustrating a drainage used for a transect to sample an erosional scar, near Questa, New Mexico. (Photograph taken by Paul Briggs.)



Figure 4. Photograph of Sugar Shack Middle and Old Sulphur Gulch waste-rock piles illustrating their size and relief, and showing benches where sampling transects were located, Molycorp Questa mine, New Mexico. These waste-rock piles are closest to the Red River. (Photograph taken by Paul Briggs.)

amount of sample mass collected was determined according to the approach of Pitard (1993) and Gy (1998).

Another sampling error that was addressed is the grouping and segregation error (GSE), which occurs because not all particles are randomly distributed. The GSE can be minimized by collecting random samples and by collecting multiple increments (that is, subsamples). In this study, subsamples were randomly collected at predetermined distances along a transect, and each multi-increment sample consists of at least 30 increments (subsamples).

Laboratory Leaching Procedures

Leaching procedures were conducted to identify and constrain the amounts of soluble constituents that could be released from the waste-rock and scar materials during rainstorms and snowmelt. After being air-dried, mixed, and dry sieved, the <2-mm-size fraction of the multi-increment samples collected from the mine waste-rock piles and the natural scar areas were subjected to two back-to-back leaching procedures. The first procedure is the USGS Field Leach Test (FLT) described in Hageman (2005, 2007) and Hageman and Briggs (2000). The FLT can be performed in the field or in the laboratory. Because of the need for air drying and mixing and the use of back-to-back leaching procedures, the FLT was performed in the laboratory. The FLT is a simple, short-duration test that addresses the readily soluble material. The FLT was followed by an 18-hour end-over-end rotation leaching procedure. The 18-hour procedure involves a longer reaction period with end-over-end rotation that results in particle-size reduction. This 18-hour procedure is similar to the USEPA method 1312 (Synthetic Precipitation Leaching Procedure [SPLP]; U.S. Environmental Protection Agency, 2004), except that deionized water was used as the leaching solution instead of a dilute $\text{H}_2\text{SO}_4/\text{HNO}_3$ solution, and a 0.45- μm nitrocellulose filter was used instead of a glass-fiber filter.

In the FLT, 100.0 g of each <2-mm sample was placed in a plastic bottle, and 2 L of deionized water was added. The solid-to-liquid leaching ratio is 1:20, the same ratio used in the USEPA methods 1311 and 1312 (U.S. Environmental Protection Agency, 2004). Each plastic bottle was capped, shaken vigorously for 5 minutes, and allowed to settle undisturbed for 10 minutes. Approximately 100 mL of each leachate was then removed for pH and specific-conductance measurements and for chemical analysis. Next, the bottles were recapped, placed on an end-over-end rotator for 18 hours, removed, and allowed to settle. A portion of the leachates was again removed for pH and specific-conductance measurements and for chemical analysis. Subsamples for chemical analysis from the two leaching procedures were filtered through a 0.45- μm nitrocellulose filter and either acidified with ultrapure nitric acid to pH <1 for analysis by inductively coupled plasma-atomic emission spectrometry (ICP–AES) and inductively coupled plasma-mass spectrometry (ICP–MS) or refrigerated for analysis by ion chromatography (IC).

Analytical Methods for Solid Samples

Prior to laboratory analysis of the bulk material, the <2-mm fraction of the samples was pulverized to 100 mesh (<0.15 mm) using a Braun vertical pulverizer equipped with ceramic plates. A subsample of the 100-mesh material was decomposed in a four-acid mixture of hydrochloric, nitric, perchloric, and hydrofluoric acids (Crock and others, 1983) and analyzed by ICP–AES (Briggs, 2002a). Total sulfur was determined on a subsample of the 100-mesh material by combustion in an oxygen atmosphere with infrared detection of evolved SO_2 (Brown and Curry, 2002).

The Rietveld method was used for semiquantitative mineralogical determinations. This method is a refinement of “routine” X-ray diffraction (XRD), which is usually based on a single peak or small subset of all of the peaks in the diffraction pattern. The Rietveld method uses all of the lines in the diffraction pattern, or even the total pattern, including the background. This method requires knowledge of the approximate crystal structure of all phases of interest in a mixture. The method consists of fitting the complete experimental diffraction pattern with calculated profiles and backgrounds and obtaining quantitative phase information from the scale factors for each phase in a mixture. In this study, samples were micronized in a micronizing mill to an average grain size of about 5 μm . An internal standard of Al_2O_3 with an average grain size of 1 μm was added (15 percent by weight) to allow quantification of amorphous material. The XRD patterns were collected on a Scintag X-1 theta-theta diffractometer (Cu K-alpha radiation, Peltier counter) with a 2-mm divergence slit and 4-mm scatter slit for the tube and a 0.5-mm scatter slit and 0.2-mm receiving slit for the detector. Patterns were scanned from 4 to 75 degrees 2-theta with a step size of 0.02-degree 2-theta and a counting time of 2 seconds per step with a sample spinner to reduce preferred orientation. The subsequent quantitative refinements were carried out using version 2.5 of the Siroquant Rietveld full-profile phase quantification program (Taylor, 1991). Relative standard deviation is about ± 3 percent for major phases ranging to ± 30 percent for trace phases (≤ 3 percent). This method is quantitative, but because of the presence of clay minerals, numbers are reported as semiquantitative.

Analytical Methods for Leachates

Filtered (0.45 μm) acidified leachates were analyzed by ICP–AES (Briggs, 2002b) and ICP–MS (Lamothe and others, 2002). Filtered (0.45 μm) refrigerated leachates were analyzed for sulfate and chloride by IC using a Dionex DX–120 (Brinton and others, 1995). Fluoride concentrations were determined using an ion-selective electrode (ISE).

For analysis of sulfur isotopes in waste-rock leachates, soluble sulfate in the filtered (0.45 μm) leachates was precipitated as barium sulfate. Precipitation was accomplished by first using a few drops of 6N HCl to adjust the pH of each sample to between pH 3 and pH 4. The samples were then

heated and stirred to near boiling, at which point 10 to 20 mL of 0.5 M BaCl₂ solution was added to each sample to precipitate BaSO₄. Heating and stirring continued for 30 minutes, then the samples sat overnight before filtration. Sulfur-isotope analyses were performed on the precipitated BaSO₄ by combustion using continuous-flow methods described by Giesemann and others (1994) with a Carlo Erba NC2500 elemental analyzer coupled to a Micromass Optima isotope-ratio mass spectrometer. Sulfur-isotope values are reported as normal δ notation relative to the standard Canyon Diablo troilite (CDT) with a standard deviation of ± 0.2 parts per thousand (per mill [‰]).

Mineralogy Data

Semiquantitative mineralogy of samples from the mine waste-rock piles and erosional scars is given in table 1 and figures 5 and 6. These data also are discussed in Briggs and others (2003). The mineralogical data are consistent with the findings of Livo and Clark (2002a, 2002b) and Livo and Knepper (2004) that a quartz-sericite-pyrite (QSP) alteration signature overprinted by a supergene weathering signature accounts for most of the surfaces of the mine waste-rock piles and erosional-scar areas. The term “sericite” is used in this report to refer to various grain sizes of muscovite and illite. During supergene weathering, pyrite and other sulfides are converted to jarosite and gypsum, and feldspar is converted to kaolinite and alunite. The presence of jarosite reflects acidic conditions (Dutrizac and Jambor, 2000; Nordstrom and Alpers, 1999; Swayze and others, 2000). As shown in table 1 and figures 5 and 6, quartz, mica (likely sericite), and X-ray amorphous material are the most abundant constituents both on the waste-rock piles and on the erosional scars. All of the waste-rock piles and scars contain jarosite (ranging between 3 and 8 weight percent) and, with one exception, gypsum (ranging between 1 and 12 weight percent; the exception is the Hottentot scar). Kaolinite was not detected in any samples from the waste-rock piles but was present in six of nine samples from the scars. Pyrite was detected in all of the waste-rock piles but in only two of the scars. The absence of pyrite and presence of kaolinite in most of the scars indicates that supergene weathering may be more intense at the scar areas compared with weathering in the waste-rock piles. The sample from the less-altered site contains no detectable gypsum, pyrite, or kaolinite but does contain detectable jarosite and hematite, with major quartz, plagioclase, and mica. The tailings sample is composed of quartz, feldspar, and amorphous material with no detectable pyrite and jarosite, relatively low mica, and minimal kaolinite.

Three of the mine waste-rock piles (Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South) contain a smectite/mica mixed phase, which could consist of either smectite/muscovite or smectite/illite. These three piles also contain more pyrite, gypsum, plagioclase, potassium feldspar, smectite, and chlorite and less quartz and amorphous material than the other two piles. The Old Sulphur Gulch and Sugar Shack Middle piles are shown in figure 4. It appears that these

three piles contain different source material than the Sugar Shack West and Capulin piles. Livo and Clark (2002a) noted that, during open-pit mining, rock extracted from the top of the system would have been dumped topographically high. If that is the case, then it is likely that the Capulin and Sugar Shack West piles would have received material extracted near the top of the system, and Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South piles would have received material extracted lower in the system. This scenario is consistent with the mine waste-rock pile history (previously discussed) in that the Sugar Shack West and Capulin waste-rock piles are among the oldest piles constructed during open-pit mining and are older than the three roadside waste-rock piles (Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South).

The Goat Hill scar (just west of the waste-rock piles; see fig. 1) contains the most mica of all the samples, considerable jarosite and kaolinite, and no detectable pyrite. These observations are consistent with the observation of Livo and Clark (2002b) that the unmined Goat Hill Gulch area appears to be more hydrothermally altered than the scars to the east. The scar at Hansen Creek also stands out in that it has the lowest mica content and highest kaolinite content, which is consistent with the observations of Livo and Clark (2002b).

Bulk Chemistry Data

Bulk chemical analyses of samples from the mine waste-rock piles and erosional scars are given in table 2 and figures 7, 8, 9, and 10. These data also are discussed in Briggs and others (2003). In preparing figures 7–10, less-than (<) values shown in table 2 were replaced with 50 percent of their value. The geometric means were also calculated using 50 percent of the value of less-than data. Comparison of the geometric means (table 2) of the bulk chemistry constituents reveals that the mine waste-rock piles are ≥ 20 percent higher than the erosional scars in Ca, Na, Ti, S, Ba, Be, Cu, Mn, Mo, Ni, Sr, Th, Y, and Zn. The erosional scars have fairly wide concentration ranges for some elements, but their geometric mean is ≥ 20 percent higher than the mine waste-rock piles in iron, phosphorus, and lead.

Comparison of the bulk chemical composition of the waste-rock piles shown in figures 7 and 8 indicates that the Capulin and Sugar Shack West piles are different from the other three piles (Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South). In particular, the Capulin and Sugar Shack West piles are lower in Ca, Fe, Mg, Na, P, Ti, and S (fig. 7) and lower in Co, Cr, Cu, Li, Mn, Mo, Ni, Sc, Sn, Sr, and V (fig. 8). This trend is consistent with the mineralogy data discussed previously and indicates that the source material for the Capulin and Sugar Shack West piles is different. Hence, both the mineralogical data and the bulk chemistry data indicate that it is likely that the Capulin and Sugar Shack West piles received material extracted near the top of the system, whereas Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South piles received material extracted lower in

Table 1. Semiquantitative mineralogy for composited mine waste-rock pile and erosional-scar samples, Questa, New Mexico.

[All results are as weight percent; ND, not detected by X-ray diffraction; <, less than]

	Mine waste-rock piles					Erosional scar sites										Less-altered site ¹	Tailings ²
	Capulin	Sugar Shack West	Old Sulphur Gulch	Sugar Shack Middle	Sugar Shack South	Goat Hill West	Goat Hill	Sulphur Gulch	SW Hansen Creek	Hansen Creek	Straight Creek	SE Straight Creek	Hottentot Creek	June Bug			
Quartz	35	40	27	25	32	27	36	24	26	35	34	30	30	35	38	36	
Mica	12	13	11	10	12	10	18	6	10	5	10	13	15	10	9	6	
Plagioclase	6	6	9	10	7	5	7	6	9	5	7	10	3	6	12	9	
K-spar	3	4	5	5	6	3	3	ND	ND	2	1	ND	1	3	2	6	
Pyrite	<1	<1	<1	1	1	<1	ND	ND	ND	<1	ND	ND	ND	ND	ND	ND	
Chlorite	8	3	10	11	8	10	<1	3	9	1	3	8	7	4	2	5	
Kaolinite	ND	ND	ND	ND	ND	ND	4	<1	ND	5	4	ND	1	2	ND	<1	
Smectite ³	ND	ND	1	2	2	ND	2	8	8	1	2	5	1	1	2	ND	
Smectite/Mica ⁴	ND	ND	2	3	3	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	
Gypsum	5	3	7	8	6	1	2	12	12	10	8	9	ND	8	ND	2	
Jarosite	4	6	6	5	5	8	7	6	5	3	3	5	5	3	2	ND	
Hematite	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	ND	2	ND	
Amorphous	26	23	21	20	17	34	21	35	21	34	28	20	37	28	31	34	

¹ Less-altered drainage west of SW Hansen Creek.

² Columbine Terrace tailings slurry-pipe sample.

³ Probably montmorillonite.

⁴ Smectite/muscovite or smectite/illite.

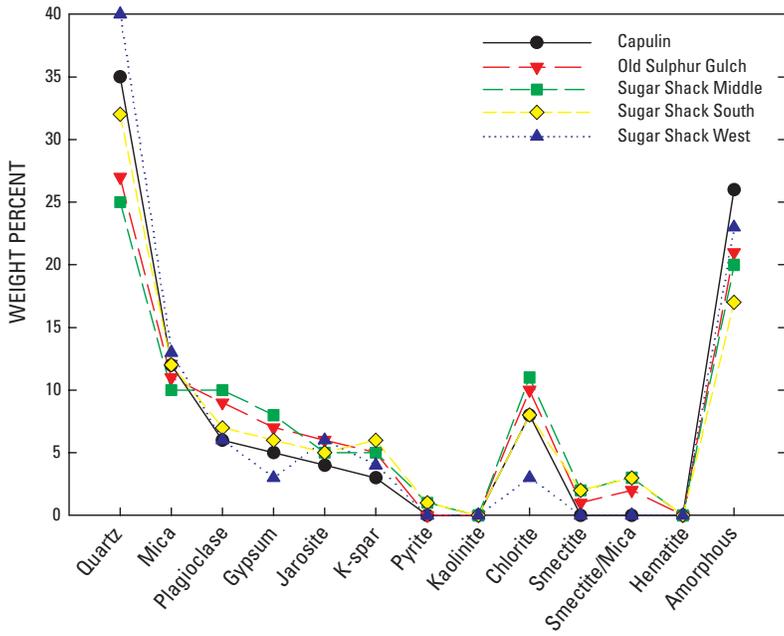


Figure 5. Semiquantitative mineralogy for composited mine waste-rock pile samples from the Questa Mine, New Mexico.

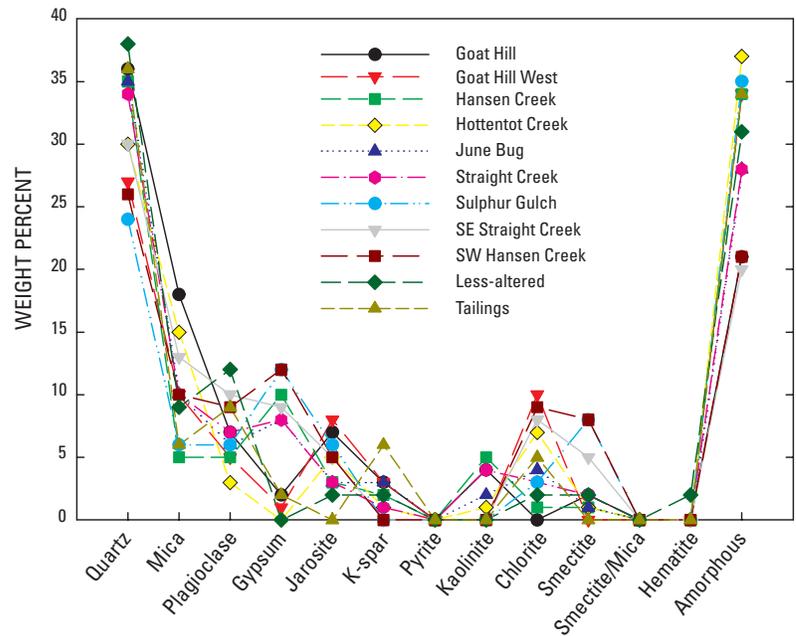


Figure 6. Semiquantitative mineralogy for composited erosional-scar samples, a less-altered sample, and a tailings sample near Questa, New Mexico.

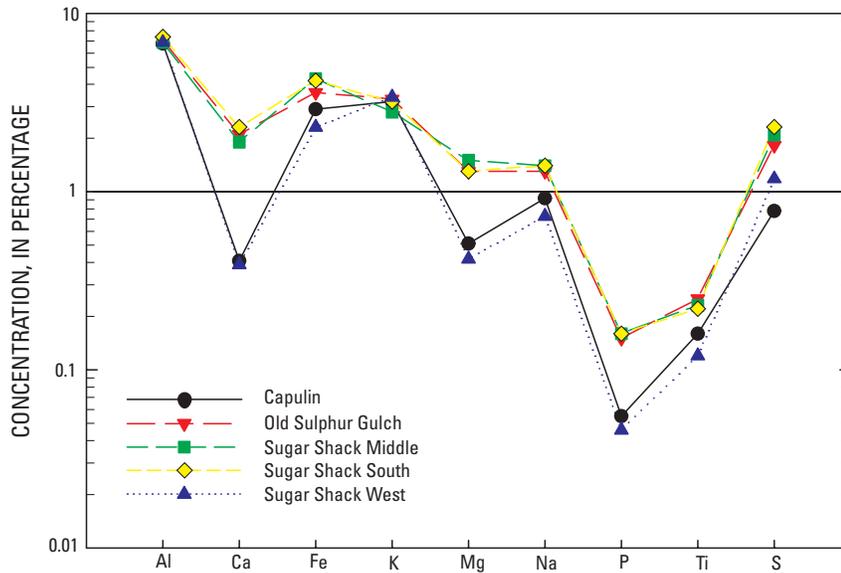


Figure 7. Bulk major-element chemical analyses for composited mine waste-rock pile samples from the Questa Mine, New Mexico.

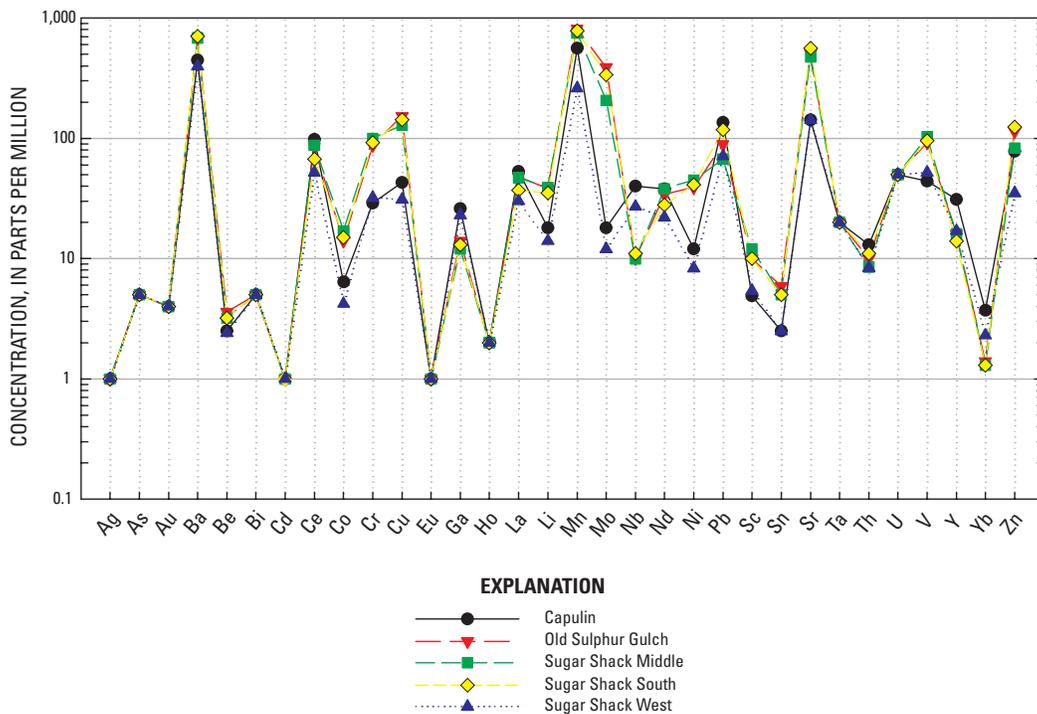


Figure 8. Bulk minor- and trace-element chemical analyses for composited mine waste-rock pile samples from the Questa Mine, New Mexico.

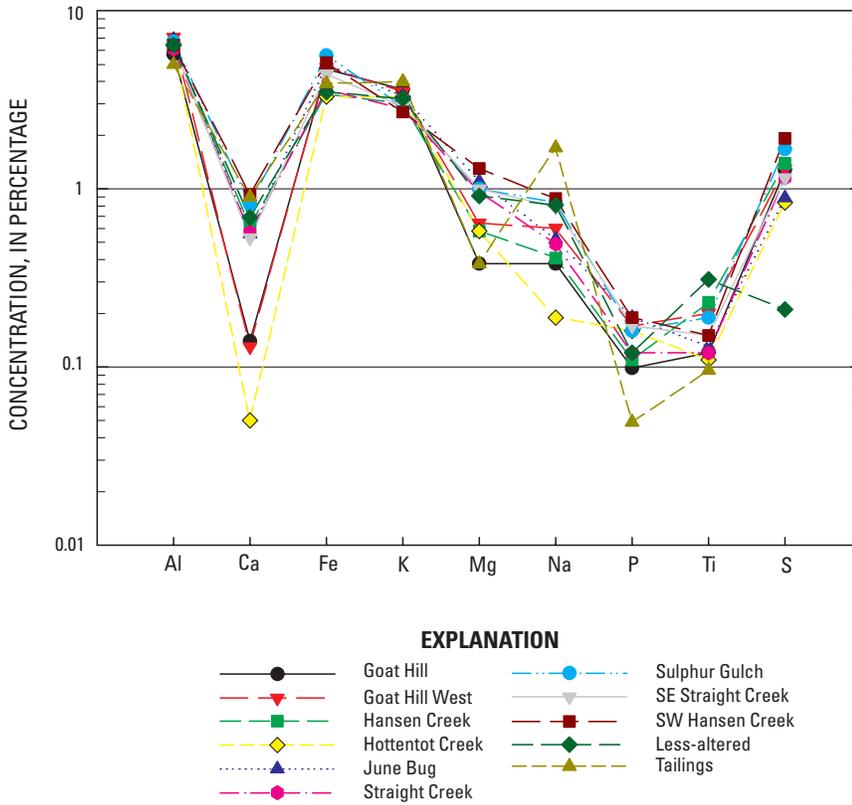


Figure 9. Bulk major-element chemical analyses for composited erosional-scar samples, a less-altered sample, and a tailings sample near Questa, New Mexico.

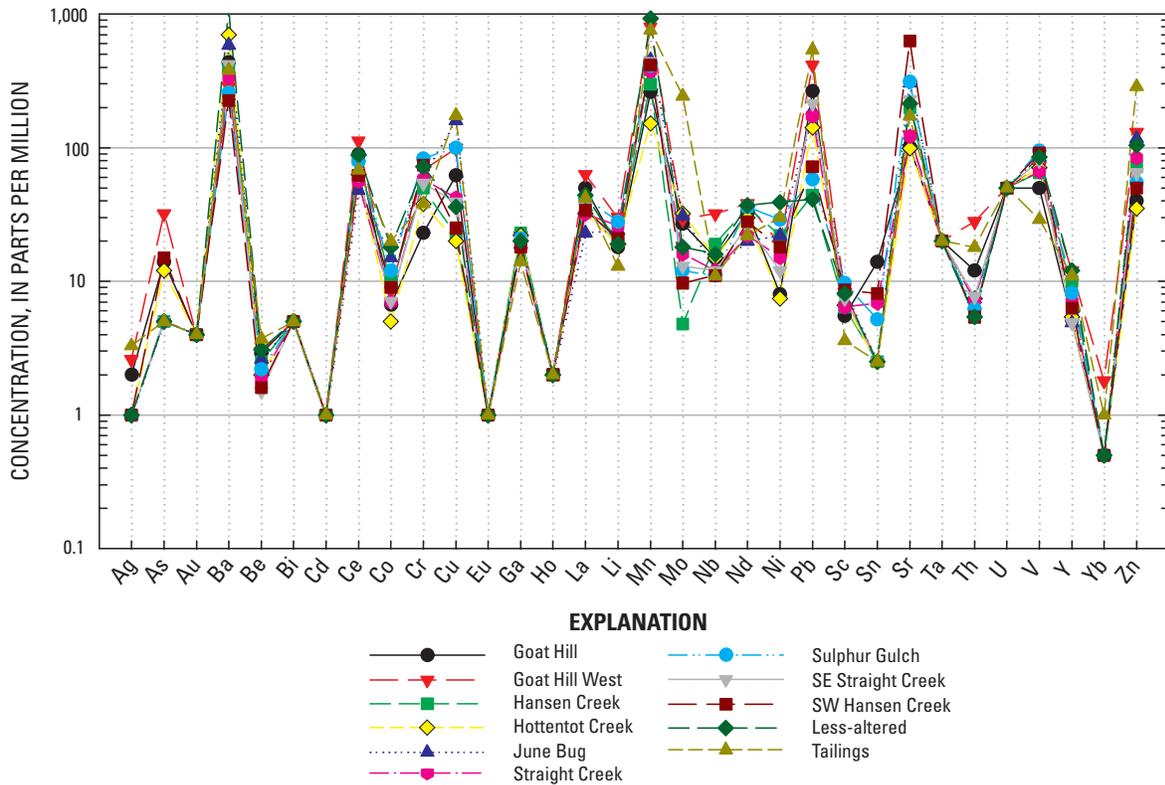


Figure 10. Bulk minor- and trace-element chemical analyses for composited erosional-scar samples, a less-altered sample, and a tailings sample near Questa, New Mexico.

Table 2. Bulk chemical analyses for composited erosional-scar and mine waste-rock pile samples, Questa, New Mexico.

[—, not determined; %, percentage; ppm, parts per million; <, less than]

Constituent	Erosional scar sites											
	Geometric mean	Goat Hill West	Goat Hill	Sulphur Gulch	SW Hansen Creek	Hansen Creek	Straight Creek	SE Straight Creek	Hottentot Creek	June Bug	Less-altered site ¹	Tailings ²
Al %	6.4	7.1	5.7	6.7	6.4	6.3	6.1	6.4	6.5	6.9	6.4	5.0
Ca %	.35	.13	.14	.82	.93	.62	.57	.53	.05	.56	.69	.90
Fe %	4.4	4.8	4.7	5.6	5.1	3.4	3.6	4.4	3.3	5.0	3.5	3.9
K %	3.1	3.5	3.6	2.9	2.7	3.0	2.8	2.9	3.3	3.3	3.2	4.0
Mg %	.78	.64	.38	1.0	1.3	.58	.96	1.0	.58	1.1	.91	.38
Na %	.52	.60	.38	.84	.88	.41	.49	.79	.19	.52	.81	1.7
P %	.15	.17	.099	.16	.19	.11	.12	.17	.16	.19	.12	.049
Ti %	.15	.20	.12	.19	.15	.23	.12	.15	.11	.13	.31	.096
S %	1.2	1.3	1.3	1.7	1.9	1.4	1.2	1.2	.84	.89	.21	—
Ag ppm	—	2.6	2.0	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	3.3
As ppm	—	32	14	< 10	15	< 10	< 10	< 10	12	< 10	< 10	< 10
Au ppm	—	< 8	< 8	< 8	< 8	< 8	< 8	< 8	< 8	< 8	< 8	< 8
Ba ppm	380	286	435	258	226	396	336	419	699	585	1,050	381
Be ppm	2.2	3.0	2.9	2.2	1.6	2.5	1.9	1.5	2.0	2.6	3.1	3.7
Bi ppm	—	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10	< 10
Cd ppm	—	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Ce ppm	70	110	89	79	62	82	56	63	63	48	88	68
Co ppm	8.5	8.5	6.7	12	9.0	10	7.0	7.1	5.0	15	18	20
Cr ppm	53	68	23	83	74	50	58	54	38	61	72	38
Cu ppm	49	99	62	100	25	22	42	39	20	160	36	170
Eu ppm	—	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2	< 2
Ga ppm	20	22	22	21	18	23	18	20	22	19	20	14
Ho ppm	—	< 4	< 4	< 4	< 4	< 4	< 4	< 4	< 4	< 4	< 4	< 4
La ppm	38	63	50	42	34	39	32	36	32	23	44	42
Li ppm	23	30	18	28	21	21	26	19	19	24	19	13
Mn ppm	367	802	261	408	417	299	373	441	152	455	925	758
Mo ppm	16	29	27	12	9.7	4.8	16	13	32	31	18	244
Nb ppm	15	32	15	11	11	19	12	12	15	12	16	11
Nd ppm	29	38	33	36	28	36	22	26	30	20	37	22
Ni ppm	15	19	8.0	29	18	22	15	12	7.4	22	39	30
Pb ppm	140	420	270	58	72	44	170	210	140	190	41	540
Sc ppm	7.4	8.3	5.5	9.7	8.6	6.4	6.4	7.4	6.6	8.4	8.1	3.6
Sn ppm	—	< 5	14	5.2	8.1	< 5	6.9	< 5	< 5	< 5	< 5	< 5
Sr ppm	195	125	101	311	626	199	121	228	99.0	304	213	172
Ta ppm	—	< 40	< 40	< 40	< 40	< 40	< 40	< 40	< 40	< 40	< 40	< 40

Table 2. Bulk chemical analyses for composited erosional-scar and mine waste-rock pile samples, Questa, New Mexico.—Continued

[—, not determined; %, percentage; ppm, parts per million; <, less than]

Erosional scar sites												
Constituent	Geometric mean	Goat Hill West	Goat Hill	Sulphur Gulch	SW Hansen Creek	Hansen Creek	Straight Creek	SE Straight Creek	Hottentot Creek	June Bug	Less-altered site ¹	Tailings ²
Th ppm	8.4	28	12	6.2	5.4	5.8	7.2	7.7	7.4	7.4	5.4	18
U ppm	—	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100	< 100
V ppm	74	72	50	95	91	65	66	80	71	85	85	29
Y ppm	6.8	12	5.2	8.2	6.3	10	7.0	4.9	5.4	4.9	12	11
Yb ppm	—	1.8	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	< 1	1.0
Zn ppm	66	130	40	55	50	72	84	65	35	120	100	290

Mine waste-rock piles							
Constituent	Geometric mean (all)	Geometric mean ³	Capulin	Sugar Shack West	Old Sulphur Gulch	Sugar Shack Middle	Sugar Shack South
Al %	7.0	6.8	6.8	6.9	7.1	6.9	7.4
Ca %	1.1	.40	.41	.39	2.1	1.9	2.3
Fe %	3.4	2.6	2.9	2.3	3.6	4.3	4.2
K %	3.2	3.3	3.2	3.4	3.3	2.8	3.2
Mg %	.89	.46	.51	.42	1.3	1.5	1.3
Na %	1.1	.82	.92	.73	1.3	1.4	1.4
P %	.10	.05	.055	.046	.15	.16	.16
Ti %	.19	.14	.16	.12	.25	.23	.22
S %	1.5	1.0	.78	1.2	1.8	2.1	2.3
Ag ppm	—	—	< 2	< 2	< 2	< 2	< 2
As ppm	—	—	< 10	< 10	< 10	< 10	< 10
Au ppm	—	—	< 8	< 8	< 8	< 8	< 8
Ba ppm	566	421	447	397	680	684	704
Be ppm	2.9	2.4	2.5	2.4	3.6	3.2	3.2
Bi ppm	—	—	< 10	< 10	< 10	< 10	< 10
Cd ppm	—	—	< 2	< 2	< 2	< 2	< 2
Ce ppm	76	71	98	52	85	87	67
Co ppm	9.9	5.2	6.4	4.2	14	17	15
Cr ppm	59	30	29	32	87	100	92
Cu ppm	82	37	43	31	150	130	140

Table 2. Bulk chemical analyses for composited erosional-scar and mine waste-rock pile samples, Questa, New Mexico.—Continued

[—, not determined; %, percentage; ppm, parts per million; <, less than]

Constituent	Mine waste-rock piles						
	Geometric mean (all)	Geometric mean ³	Capulin	Sugar Shack West	Old Sulphur Gulch	Sugar Shack Middle	Sugar Shack South
Eu ppm	—	—	< 2	< 2	< 2	< 2	< 2
Ga ppm	17	24	26	23	14	12	13
Ho ppm	—	—	< 4	< 4	< 4	< 4	< 4
La ppm	42	40	53	30	48	47	37
Li ppm	27	16	18	14	38	39	35
Mn ppm	588	383	561	261	816	751	781
Mo ppm	90	15	18	12	390	210	340
Nb ppm	16	33	40	27	10	9.9	11
Nd ppm	31	29	38	22	34	38	28
Ni ppm	23	10	12	8.3	39	45	41
Pb ppm	92	98	140	71	89	67	120
Sc ppm	7.9	5.1	4.9	5.4	10	12	10
Sn ppm	—	—	< 5	< 5	5.9	5.0	5.0
Sr ppm	307	142	142	142	505	477	560
Ta ppm	—	—	< 40	< 40	< 40	< 40	< 40
Th ppm	10	10	13	8.4	10	8.5	11
U ppm	—	—	< 100	< 100	< 100	< 100	< 100
V ppm	73	48	44	52	92	100	95
Y ppm	18	23	31	17	16	16	14
Yb ppm	1.8	2.9	3.7	2.3	1.4	1.3	1.3
Zn ppm	80	52	78	35	110	83	120

¹ Less-altered drainage west of SW Hansen Creek.

² Columbine Terrace tailings slurry-pipe sample.

³ Geometric mean for Capulin and Sugar Shack West mine waste-rock piles only.

the system. Accordingly, the Capulin and Sugar Shack West piles likely are more similar to the scars than are the other three piles.

Comparison of the geometric means of the bulk chemistry constituents for only Capulin and Sugar Shack West (see table 2) with the geometric means for the scars reveals that these two mine waste-rock piles are ≥ 20 percent higher than the erosional scars in Na, Nb, Th, and Y. The erosional scars have fairly wide concentration ranges for some elements, but their geometric mean is ≥ 20 percent higher than the Capulin and Sugar Shack West waste-rock piles in Fe, Mg, P, S, Co, Cr, Cu, Li, Ni, Sc, Sr, V, and Zn. It appears that the scar samples are higher in iron, sulfur, and several base metals than are the Capulin and Sugar Shack West piles.

The bulk chemical composition of the scar samples shown in figures 9 and 10 displays fairly wide concentration ranges but little deviation from the trends. The scars at Hottentot, Goat Hill West, and Goat Hill all have low calcium values in comparison with the other scars. The scar at Hottentot also stands out in that it has lower cobalt, nickel, and zinc than the other scars.

The USGS has chosen the Straight Creek drainage (fig. 1) as an analog site to provide information about pre-mining geochemical conditions at the Questa Mine. Comparison of the geometric means for bulk chemistry of mine waste-rock piles with the bulk chemistry of the Straight Creek scar area is given in table 3. The mine waste-rock piles are ≥ 20 percent higher than Straight Creek in Ca, Na, Ti, S, Ba, Be, Ce, Co, Cu, La, Mn, Mo, Nb, Nd, Ni, Sc, Sr, Th, and Y. Lead is the only element in Straight Creek bulk material that exceeds the waste-rock piles by ≥ 20 percent.

Overview of Leaching Study Applications

The < 2 -mm multi-increment samples from the five mine waste-rock piles, nine erosional-scar areas, a less-altered site, and a tailings slurry-pipe sample were subjected to two back-to-back leaching procedures. The first procedure, the FLT, is of short duration (5-minute shaking and 10-minute settling) and is intended to leach readily soluble materials. The FLT was immediately followed by an 18-hour end-over-end rotation leaching procedure, which is similar to the USEPA 1312 procedure (U.S. Environmental Protection Agency, 2004). The end-over-end rotation results in considerable particle-size reduction over the course of the procedure. These leaching procedures can be used to qualitatively evaluate potential metal and acid release to receiving streams and shallow ground water. In addition, they can provide qualitative information about the likely chemical composition of porewater within the waste-rock piles and erosional scars. Finally, these back-to-back procedures can lend insight into reactions that may take place upon migration of porewater through changing geochemical conditions (for example, pH changes) both within

the waste-rock and scar materials and away from the source materials. However, these (or any) leaching procedures cannot provide quantitative concentrations of actual waste-rock or scar contributions to surface or ground water. The leaching procedures employed in this study use a 1:20 solid-to-water ratio. This same ratio is used in the USEPA 1311 and 1312 tests (U.S. Environmental Protection Agency, 2004) and is dilute enough to alleviate most issues with solubility controls during the leaching procedures.

Mine Waste-Rock Leaching Results

For preparation of graphs, data points with qualified values were replaced with a value equal to 50 percent of the detection limit. Table 4 lists chemical analyses for leachates from the mine waste-rock piles. The pH of the waste-rock leachates vary between 3.0 (Sugar Shack West) and 6.2 (Old Sulphur Gulch). With the exception of Sugar Shack West, the pH rises between the FLT and the 18-hour test; figure 11 illustrates this trend. It seems that the higher the FLT pH, the greater the pH increase during the 18-hour test. Some of the pH increases are as much as 1 pH unit. It appears that the increased time and increased agitation, which result in particle-size reduction, are able to expose minerals (for example, calcite) that can buffer the pH of the leachate solutions. All of the mine waste-rock leachates exhibit an increase in specific conductance and sulfate concentration between the FLT and the 18-hour procedure. These increases are illustrated in figure 12. There is also an increase in calcium concentration between the FLT and the 18-hour procedure (table 4), indicating dissolution of gypsum with increased time and agitation. Robertson GeoConsultants, Inc. (2000b), noted a solubility control by gypsum for mine waste-rock leachates at a concentration of about 2,000 mg/L sulfate (SO_4). Sulfate data in this study do not exceed 1,500 mg/L SO_4 , so solubility control by gypsum does not appear to be a factor. Also, results from solubility calculations for the leachates using WATEQ4F (Ball and Nordstrom, 1991) do not indicate that saturation with respect to gypsum occurred in the leachates. Assuming stoichiometric dissolution, calculations indicate that nearly all of the sulfate in the Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South piles can be explained by gypsum dissolution. For the Capulin and Sugar Shack West piles, 57 percent and 39 percent, respectively, of the leachate sulfate can be attributed to gypsum dissolution. There is excess calcium concentration in leachates from the three younger roadside piles (Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South), which indicates that calcium dissolution, in addition to gypsum dissolution, is taking place in those three piles.

In the mine waste-rock leachates, some elements increased in concentration between the FLT and 18-hour procedure, and others decreased. For most samples, the elements that increased over the 18-hour leaching period include Ca, Cd, K, Mg, Mn, Mo, Rb, Si, Sr, and Ti. The elements that

Table 3. Comparison of the geometric means of bulk chemical analyses for composited mine waste-rock pile material with the bulk chemical analysis of the Straight Creek erosional-scar area, Questa, New Mexico.

[—, not determined; %, percentage; ppm, parts per million; <, less than]

Constituent	Geometric mean of mine waste-rock piles ¹	Straight Creek	Ratio
Al %	7.0	6.1	1.2
Ca %	1.1	.57	1.9
Fe %	3.4	3.6	.94
K %	3.2	2.8	1.1
Mg %	.89	.96	.92
Na %	1.1	.49	2.3
P %	.10	.12	.83
Ti %	.19	.12	1.6
S %	1.5	1.2	1.3
Ag ppm	—	< 2	—
As ppm	—	< 10	—
Au ppm	—	< 8	—
Ba ppm	570	340	1.7
Be ppm	2.9	1.9	1.5
Bi ppm	—	< 10	—
Cd ppm	—	< 2	—
Ce ppm	76	56	1.4
Co ppm	9.9	7.0	1.4
Cr ppm	59	58	1.0
Cu ppm	82	42	2.0
Eu ppm	—	< 2	—
Ga ppm	17	18	.93
Ho ppm	—	< 4	—
La ppm	42	32	1.3
Li ppm	27	26	1.0
Mn ppm	590	370	1.6
Mo ppm	90	16	5.6
Nb ppm	16	12	1.4
Nd ppm	31	22	1.4
Ni ppm	23	15	1.6
Pb ppm	92	170	.53
Sc ppm	7.9	6.4	1.2
Sn ppm	—	6.9	—
Sr ppm	310	120	2.5
Ta ppm	—	< 40	—
Th ppm	10	7.2	1.4
U ppm	—	< 100	—
V ppm	73	66	1.1
Y ppm	18	7	2.6
Yb ppm	1.8	< 1	—
Zn ppm	80	84	.95

¹ Geometric mean of five mine waste-rock piles listed in table 2.

Table 4. Leachate chemical analyses for composited mine waste-rock pile samples, Questa, New Mexico.

[Analyzed by ICP-MS unless otherwise noted; —, not determined; Sp. Cond., specific conductance; $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $\mu\text{g}/\text{L}$, micrograms per liter; mg/L , milligrams per liter; %, percentage; <, less than; ‰, parts per thousand]

Property or constituent ¹	18-hour test						
	Geometric mean ²	Capulin	Old Sulphur Gulch	Sugar Shack Middle	Sugar Shack South	Sugar Shack West	Tailings ³
pH	4.9	4.1	6.2	5.6	5.7	3.0	7.0
Sp. Cond. $\mu\text{S}/\text{cm}$	1,470	609	1,840	1,770	2,050	1,070	259
Ag $\mu\text{g}/\text{L}$	—	<3	<3	<3	<3	<3	< 3
Al* mg/L	1.4	1.7	.12	2.2	1.5	9.0	.039
As $\mu\text{g}/\text{L}$	—	<1	<1	<1	<1	2	< 1
B* mg/L	.021	.032	.013	.012	<0.01	.041	—
Ba $\mu\text{g}/\text{L}$	70	80	76	77	46	76	48
Be $\mu\text{g}/\text{L}$	.63	3.2	.10	.40	.30	2.6	< 0.05
Ca* mg/L	280	100	510	490	620	110	49
Cd $\mu\text{g}/\text{L}$	2.6	1.4	3.4	4.6	6.2	.77	.47
Ce $\mu\text{g}/\text{L}$	17	50	2.2	12	13	93	.03
Co $\mu\text{g}/\text{L}$	30	12	18	54	60	34	.09
Cr $\mu\text{g}/\text{L}$	—	<1	<1	<1	<1	17	< 1
Cs $\mu\text{g}/\text{L}$	—	.03	.04	.04	.05	< 0.02	< 0.01
Cu $\mu\text{g}/\text{L}$	27	100	3.4	14	13	220	2.7
Dy $\mu\text{g}/\text{L}$	1.2	3.4	.12	1.3	1.1	4.2	—
Er $\mu\text{g}/\text{L}$	.48	1.2	.05	.53	.51	1.6	—
Eu $\mu\text{g}/\text{L}$	.46	.74	.07	.58	.53	1.2	—
Fe $\mu\text{g}/\text{L}$	—	<50	<50	<50	<50	16,100	< 50
Ga $\mu\text{g}/\text{L}$	.31	.82	.06	.20	.22	1.4	.03
Gd $\mu\text{g}/\text{L}$	2.2	5.9	.24	2.1	2.0	8.0	—
Ge $\mu\text{g}/\text{L}$	.10	.20	.05	.06	.08	.26	< 0.02
Ho $\mu\text{g}/\text{L}$	.20	.53	.02	.23	.22	.66	—
K* mg/L	2.5	1.4	5.4	4.0	3.7	0.8	2.3
La $\mu\text{g}/\text{L}$	8.2	23	1.6	6.6	6.4	25	.02
Li $\mu\text{g}/\text{L}$	15	6.6	14	22	23	18	.90
Mg* mg/L	11	4.1	13	18	19	7.9	.73
Mn $\mu\text{g}/\text{L}$	2,740	2,280	2,460	3,440	4,770	1,680	51.3
Mo $\mu\text{g}/\text{L}$	—	< 2	420	110	170	< 2	350
Na* mg/L	1.3	1.2	1.6	1.4	1.0	1.3	.48
Nb $\mu\text{g}/\text{L}$	—	< 0.2	< 0.2	< 0.2	< 0.2	0.21	.06
Nd $\mu\text{g}/\text{L}$	11	30	1.4	7.8	8.8	58	—
Ni $\mu\text{g}/\text{L}$	83	33	68	120	160	90	.90
P mg/L	—	< 0.01	< 0.01	< 0.01	< 0.01	.04	< 0.01
Pb $\mu\text{g}/\text{L}$	.20	.40	<0.05	.20	.10	.20	.52
Pr $\mu\text{g}/\text{L}$	2.6	7.6	0.30	1.8	1.9	14	—
Rb $\mu\text{g}/\text{L}$	4.9	2.9	9.2	8.3	8.2	1.5	2.8
Sb $\mu\text{g}/\text{L}$	.60	.44	.88	<0.3	.46	.73	.35

Table 4. Leachate chemical analyses for composited mine waste-rock pile samples, Questa, New Mexico.—Continued

[Analyzed by ICP–MS unless otherwise noted; —, not determined; Sp. Cond., specific conductance; $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $\mu\text{g}/\text{L}$, micrograms per liter; mg/L , milligrams per liter; %, percentage; <, less than; ‰, parts per thousand]

Property or constituent ¹	18-hour test						
	Geometric mean ²	Capulin	Old Sulphur Gulch	Sugar Shack Middle	Sugar Shack South	Sugar Shack West	Tailings ³
Sc $\mu\text{g}/\text{L}$	—	< 0.6	< 0.6	< 0.6	< 0.6	1.7	0.30
Se $\mu\text{g}/\text{L}$	—	1.8	< 1	< 1	1.0	1.6	< 1
Si mg/L	1.4	1.6	1.3	1.4	1.4	1.1	.70
Sm $\mu\text{g}/\text{L}$	2.1	6.5	.21	1.7	1.8	11	—
SO ₄ [*] mg/L	720	260	1,200	1,100	1,400	390	87
Sr $\mu\text{g}/\text{L}$	926	366	2,530	2,460	2,470	121	332
Tb $\mu\text{g}/\text{L}$	.26	.76	.030	.24	.24	.97	—
Th $\mu\text{g}/\text{L}$	—	< 0.2	< 0.2	< 0.2	.35	3.1	.02
Ti $\mu\text{g}/\text{L}$	8.8	3.6	14	13	16	5.4	1.2
Tl $\mu\text{g}/\text{L}$	—	< 0.1	< 0.1	< 0.1	< 0.1	.10	< 0.1
Tm $\mu\text{g}/\text{L}$	.050	.12	.006	.053	.050	.17	—
U $\mu\text{g}/\text{L}$	.51	.94	.76	.14	.32	1.1	.47
V $\mu\text{g}/\text{L}$	—	< 0.5	< 0.5	< 0.5	< 0.5	< 0.5	< 0.1
Y $\mu\text{g}/\text{L}$	7.5	14	1.3	9.0	9.2	16	.03
Yb $\mu\text{g}/\text{L}$	.22	.62	.020	.22	.22	.90	—
Zn $\mu\text{g}/\text{L}$	234	326	76.9	251	285	392	7.00
Zr $\mu\text{g}/\text{L}$	—	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
$\delta^{34}\text{S}$ ‰	—	-7.9	2.5	1.3	2.0	-5.8	—
F ^{**} mg/L	1.3	.27	2.2	4.0	3.0	.49	.75
Cl ^{**} mg/L	—	< 0.6	< 0.6	< 0.6	< 0.6	< 0.6	< 0.6
SO ₄ ^{**} mg/L	789	310	1,200	1,180	1,480	470	99.0
C.I. ⁴ %	—	-13	9.7	9.7	9.5	-8.1	22 ⁵

Table 4. Leachate chemical analyses for composited mine waste-rock pile samples, Questa, New Mexico.—Continued[Analyzed by ICP-MS unless otherwise noted; —, not determined; Sp. Cond., specific conductance; $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $\mu\text{g}/\text{L}$, micrograms per liter; mg/L , milligrams per liter; %, percentage; <, less than; ‰, parts per thousand]

Property or constituent ¹	Field Leach Test						Tailings ³
	Geometric mean ²	Capulin	Old Sulphur Gulch	Sugar Shack Middle	Sugar Shack South	Sugar Shack West	
pH	4.3	3.7	5.1	4.6	4.7	3.2	7.4
Sp. Cond. $\mu\text{S}/\text{cm}$	1,020	569	1,110	1,190	1,380	862	145
Ag $\mu\text{g}/\text{L}$	—	<3	<3	<3	<3	<3	<3
Al* mg/L	3.9	1.6	2.6	5.0	5.4	8.2	.056
As $\mu\text{g}/\text{L}$	—	<1	<1	<1	<1	<1	<1
B* mg/L	.028	.041	.017	.024	.024	.042	—
Ba $\mu\text{g}/\text{L}$	73	77	70	75	74	69	43
Be $\mu\text{g}/\text{L}$	2.1	2.4	1.3	2.8	2.8	1.6	<0.05
Ca* mg/L	180	88	260	270	340	92	22
Cd $\mu\text{g}/\text{L}$	2.1	.99	3.5	3.9	4.8	.61	.16
Ce $\mu\text{g}/\text{L}$	20	40	5.5	11	17	71	.11
Co $\mu\text{g}/\text{L}$	31	8.0	33	56	69	28	.05
Cr $\mu\text{g}/\text{L}$	—	<1	<1	<1	1.6	16	<1
Cs $\mu\text{g}/\text{L}$	.04	.04	.04	.05	.05	<0.02	.01
Cu $\mu\text{g}/\text{L}$	170	110	110	230	300	170	2.6
Dy $\mu\text{g}/\text{L}$	2.3	2.8	1.0	2.1	3.1	3.5	—
Er $\mu\text{g}/\text{L}$	.88	.92	.42	.79	1.3	1.3	—
Eu $\mu\text{g}/\text{L}$	.71	.59	.36	.75	1.2	1.0	—
Fe $\mu\text{g}/\text{L}$	—	158	<50	<50	<50	15,700	<50
Ga $\mu\text{g}/\text{L}$	.30	.55	.09	.20	.26	1.0	.02
Gd $\mu\text{g}/\text{L}$	3.3	4.9	1.3	2.6	4.0	6.5	—
Ge $\mu\text{g}/\text{L}$	—	.08	<0.05	<0.05	.07	.20	<0.02
Ho $\mu\text{g}/\text{L}$	.38	.42	.17	.36	.55	.54	—
K* mg/L	1.3	.72	3.1	2.5	2.3	.26	1.7
La $\mu\text{g}/\text{L}$	7.4	17	2.5	4.9	6.5	17.4	.06
Li $\mu\text{g}/\text{L}$	15	4.8	17	22	30	15	.60
Mg* mg/L	9.1	3.6	10	15	16	7.4	.48
Mn $\mu\text{g}/\text{L}$	1,810	1,270	1,570	2,460	2,900	1,380	54.0
Mo $\mu\text{g}/\text{L}$	—	<2	24	4.4	12	<2	95
Na* mg/L	1.2	1.2	1.1	1.1	1.4	1.1	.43
Nb $\mu\text{g}/\text{L}$	—	<0.2	<0.2	<0.2	<0.2	<0.2	.04
Nd $\mu\text{g}/\text{L}$	14	25	4.2	8.2	14	46	—
Ni $\mu\text{g}/\text{L}$	73	25	70	110	150	73	.50
P mg/L	—	<0.01	<0.01	.01	.01	.06	<0.01
Pb $\mu\text{g}/\text{L}$	.43	.69	.20	.30	.40	.88	1.0
Pr $\mu\text{g}/\text{L}$	3.2	6.2	.90	1.7	3.0	11	—
Rb $\mu\text{g}/\text{L}$	3.8	2.9	7.2	8.2	6.5	.75	2.0
Sb $\mu\text{g}/\text{L}$	—	<0.3	.38	<0.3	<0.3	<0.3	.20

Table 4. Leachate chemical analyses for composited mine waste-rock pile samples, Questa, New Mexico.—Continued

[Analyzed by ICP–MS unless otherwise noted; —, not determined; Sp. Cond., specific conductance; $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $\mu\text{g}/\text{L}$, micrograms per liter; mg/L , milligrams per liter; %, percentage; <, less than; ‰, parts per thousand]

Property or constituent ¹	Geometric mean ²	Field Leach Test					Tailings ³
		Capulin	Old Sulphur Gulch	Sugar Shack Middle	Sugar Shack South	Sugar Shack West	
Sc $\mu\text{g}/\text{L}$	—	< 0.6	< 0.6	< 0.6	< 0.6	1.0	< 0.1
Se $\mu\text{g}/\text{L}$	—	< 1	< 1	< 1	1.0	< 1	< 1
Si mg/L	—	< 0.2	.30	.20	.30	< 0.2	< 0.2
Sm $\mu\text{g}/\text{L}$	3.4	5.5	1.1	2.2	3.7	9.0	—
SO ₄ * mg/L	480	230	630	650	820	330	45
Sr $\mu\text{g}/\text{L}$	438	233	1,130	1,070	1,180	48.4	91.3
Tb $\mu\text{g}/\text{L}$	.44	.60	.18	.37	.57	.76	—
Th $\mu\text{g}/\text{L}$	—	< 0.2	< 0.2	< 0.2	< 0.2	3.6	.03
Ti $\mu\text{g}/\text{L}$	5.5	2.6	7.5	7.9	9.4	3.6	.60
Tl $\mu\text{g}/\text{L}$	—	<0.1	<0.1	<0.1	<0.1	<0.1	< 0.1
Tm $\mu\text{g}/\text{L}$	.10	.097	.050	.097	.16	.13	—
U $\mu\text{g}/\text{L}$	.94	1.2	.48	.84	1.8	.84	.08
V $\mu\text{g}/\text{L}$	—	<0.5	<0.5	<0.5	<0.5	<0.5	< 0.1
Y $\mu\text{g}/\text{L}$	11	11	5.7	10	16	13	.03
Yb $\mu\text{g}/\text{L}$	.51	.48	.25	.49	.82	.72	—
Zn $\mu\text{g}/\text{L}$	315	214	302	374	474	269	2.60
Zr $\mu\text{g}/\text{L}$	—	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2
$\delta^{34}\text{S}$ ‰	—	—	—	—	—	—	—
F** mg/L	.49	.11	.88	1.2	1.0	.23	.25
Cl** mg/L	—	<0.6	<0.6	<0.6	<0.6	<0.6	<0.6
SO ₄ ** mg/L	524	260	670	710	890	360	53.0
C.I. ⁴ %	—	-3.9	2.7	6.0	4.2	1.8	5.9 ⁶

¹ Constituents marked with an asterisk were analyzed by inductively coupled plasma-atomic emission spectroscopy (ICP–AES). Constituents marked with two asterisks were analyzed by IC. The pH, specific conductance, and sulfur isotope analytical methods are described in the text.

² Does not include Columbine Terrace tailings sample. Specific conductance and pH are arithmetic means.

³ Columbine Terrace tailings slurry-pipe sample.

⁴ Charge Imbalance (C.I.) = $100 \times (\text{sum cations} - \text{sum anions}) / [(\text{sum cations} + \text{sum anions}) / 2]$, reported as percent difference. Anion data were analyzed by Ion Chromatography.

⁵ Includes NO₃ = 1.2 mg/L.

⁶ Includes NO₃ = 1.1 mg/L.

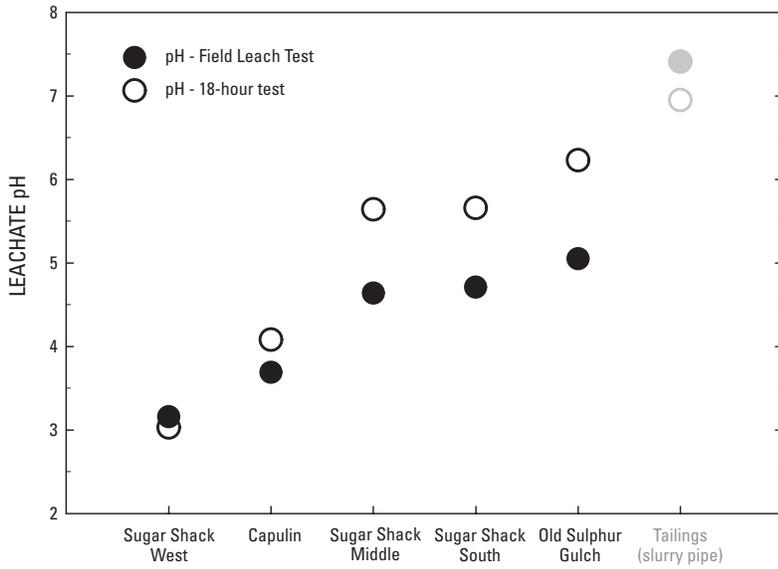
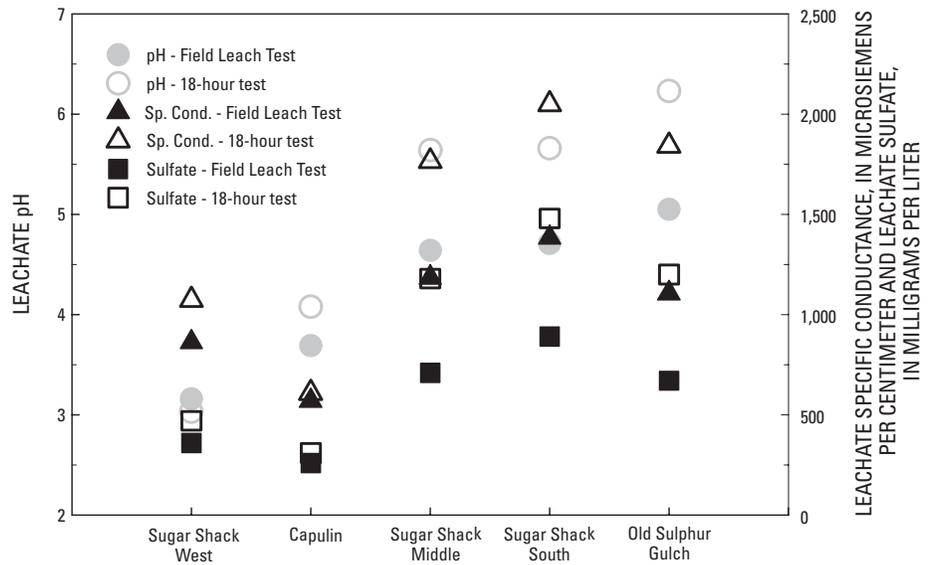


Figure 11. Leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited mine waste-rock pile samples and a tailings sample from the Questa Mine, New Mexico.

Figure 12. Leachate specific conductance, leachate sulfate concentration, and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited mine waste-rock pile samples from the Questa Mine, New Mexico. Sp. Cond., specific conductance.



decreased over the 18-hour leaching period include Al, B, Be, Cu, Dy, Er, Eu, Gd, Ho, Nd, Pb, Pr, Sm, Tb, Tm, Yb, and Zn. Figures 13 to 15 show the increase in concentration between the FLT and the 18-hour procedure for silicon, titanium, and manganese, respectively. Increases in concentration of these elements indicate that further dissolution of rock-forming minerals is taking place during the 18-hour leaching procedure.

In the mine waste-rock leachates, iron and aluminum concentrations appear to be controlled by pH-dependent solubility reactions. As seen in figure 16, Sugar Shack West has leachate pH values of 3.0 and 3.2 with approximately 16 mg/L of iron present in the leachate. However, when the Capulin leachate shifts from pH 3.7 in the FLT to 4.1 in the 18-hour procedure, iron shifts from 0.2 mg/L to below detection (less-than values were replaced with 50 percent of the detection limit in preparation of the figure). The other leachates have pH >3.7, and all have iron <0.05 mg/L (fig. 16). Nordstrom and Alpers (1999) state that schwertmannite, or other sulfate-substituted hydrous ferric oxides, are most likely to control ferric iron solubility in acid mine drainage. They note that supersaturation of iron occurs at pH values above about 4. The data from this study indicate that the pH cutoff for iron solubility is about pH 3.7. These pH-dependent solubility reactions also can be noted for aluminum. As seen in figure 17, the pH increase between the FLT and the 18-hour procedure for Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South all show a corresponding decrease in aluminum concentration. In contrast, Sugar Shack West and Capulin, which have lower pH values (pH <4.6), do not show a significant change in aluminum concentration between the FLT and 18-hour leaching procedure (less-than values were replaced with 50 percent of the detection limit in preparation of the figure). Results from solubility calculations for the leachates using WATEQ4F (Ball and Nordstrom, 1991) show that Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South are all saturated with respect to gibbsite, whereas Capulin and Sugar Shack West are not. Nordstrom and Alpers (1999) discuss the relationship between saturation indices for gibbsite as a function of pH. They explain that when acid-mine drainage is diluted by neutral-pH water, the pH and aluminum concentrations eventually reach the gibbsite solubility curve, and aluminum concentrations are controlled by the solubility of a solid phase or by a surface coating. Furthermore, for acid-mine waters with pH values above 5, solubility of dissolved aluminum is controlled by microcrystalline to amorphous $\text{Al}(\text{OH})_3$. The data in figure 17 are consistent with these pH-dependent solubility reactions and indicate solubility control above a pH of about 5.1.

Some of the elements that exhibit pH-dependent concentration reversals between the FLT and 18-hour leaching procedure may be undergoing pH-dependent coprecipitation or sorption reactions with iron or aluminum. Figures 16 and 17 show that iron and aluminum appear to be precipitating during the leaching procedures at about pH 3.7 and 5.1, respectively. Figure 18 shows a plot for copper, where leachate copper concentrations notably decrease above a leachate pH of about 6. Sorption of cations, such as copper, increases with

increasing pH, and pH 6 corresponds to the pH range in which substantial copper sorbs onto hydrous iron oxides (Smith, 1999; Smith and others, 1998). The pH-dependent sorption of copper during the 18-hour leaching procedure explains why the copper concentration is higher in the 18-hour leachates for the lower-pH samples and lower in the 18-hour leachates for the higher-pH samples. These types of pH-dependent sorption reactions also may be taking place for Be, Cd, Ce, Co, Cr, and Zn (shown in figs. 19, 20, 21, 22, 23, and 24, respectively). Conversely, figure 25 shows the relationship for molybdenum, where molybdenum concentrations increase with increasing leachate pH. This behavior is typical of anion sorption reactions, in which sorption of anions, such as molybdenum, decreases with increasing pH (Smith, 1999). These types of pH-dependent reactions are likely taking place within the porewater of the mine waste-rock piles and in water being transported away from the piles. Hence, for a given leachable metal concentration that is soluble at a given pH, a portion of that concentration may be decreased or increased as a result of pH-dependent sorption or coprecipitation reactions.

In this study, lead (fig. 26) leachate concentrations are always lower in the 18-hour leachates than in the FLT leachates. As seen in figure 12, sulfate concentrations always increase between the FLT and 18-hour leaching procedure. Hence, it appears that lead concentrations are being controlled by anglesite (PbSO_4) solubility because the common-ion effect is in operation.

The tailings sample from Columbine Terrace generates circumneutral pH leachates and generally lower element concentrations than do the mine waste-rock piles. An exception is the molybdenum concentration. The charge imbalance is unusually high for the 18-hour leachate. This is likely due to the fact that alkalinity measurements were not made on the leachates, so alkalinity is not included in the charge-balance calculations. The tailings samples from Columbine Terrace also contained measurable nitrate (data not included in table 4).

The isotopic composition of sulfate from the 18-hour leachates from the mine waste-rock piles is given in table 4 and figure 27, which shows two distinct groups. Sugar Shack West and Capulin $\delta^{34}\text{S}$ values range from -5.8 to -7.9 parts per thousand, respectively. Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South all have positive $\delta^{34}\text{S}$ values ranging from 1.3 to 2.5 parts per thousand. Mineralogy data (table 1) and bulk-chemistry data (table 2) indicate that there are compositional differences between the Capulin and Sugar Shack West piles compared to the Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South piles. If indeed the Capulin and Sugar Shack West piles received material extracted near the top of the system, then their leachate isotopic signatures should be similar to those of the erosional scars. The isotopic composition of sulfate from the 18-hour leachate from the Goat Hill West scar was measured as -2.1 parts per thousand in this study. Tuttle and others (2003) measured the isotopic composition of sulfate from Straight (-4.2 to -6.8 parts per thousand), Hottentot (-3.9 to -4.6 parts

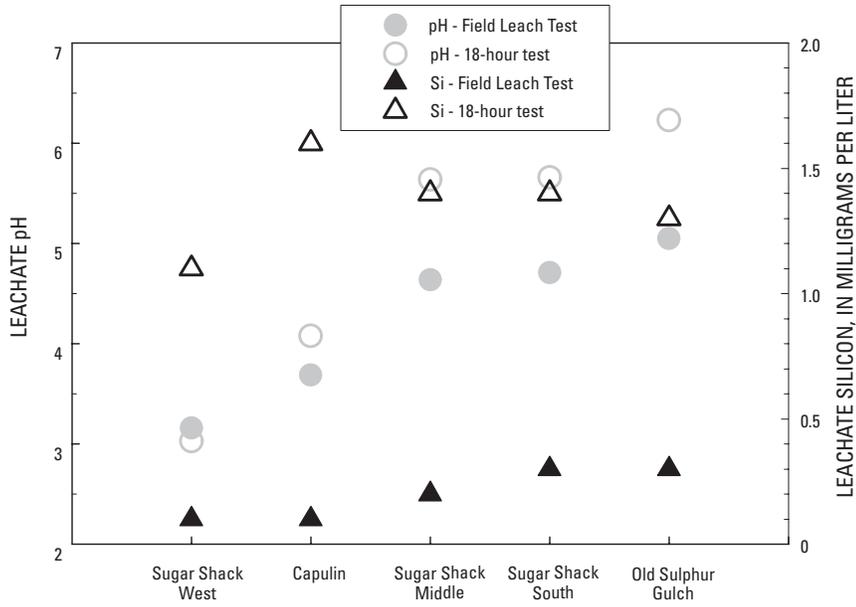
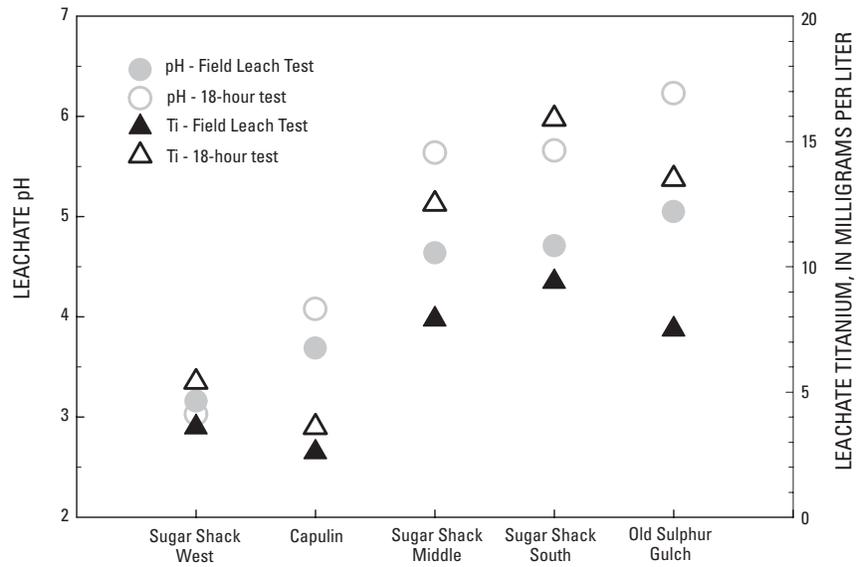


Figure 13. Leachate silicon (Si) concentration and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited mine waste-rock pile samples from the Questa Mine, New Mexico.

Figure 14. Leachate titanium (Ti) concentration and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited mine waste-rock pile samples from the Questa Mine, New Mexico.



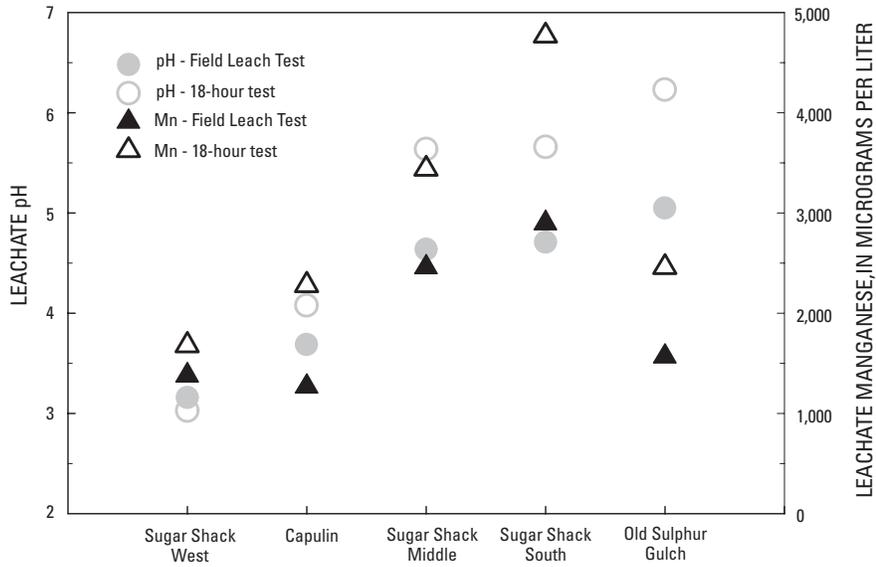


Figure 15. Leachate manganese (Mn) concentration and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited mine waste-rock pile samples from the Questa Mine, New Mexico.

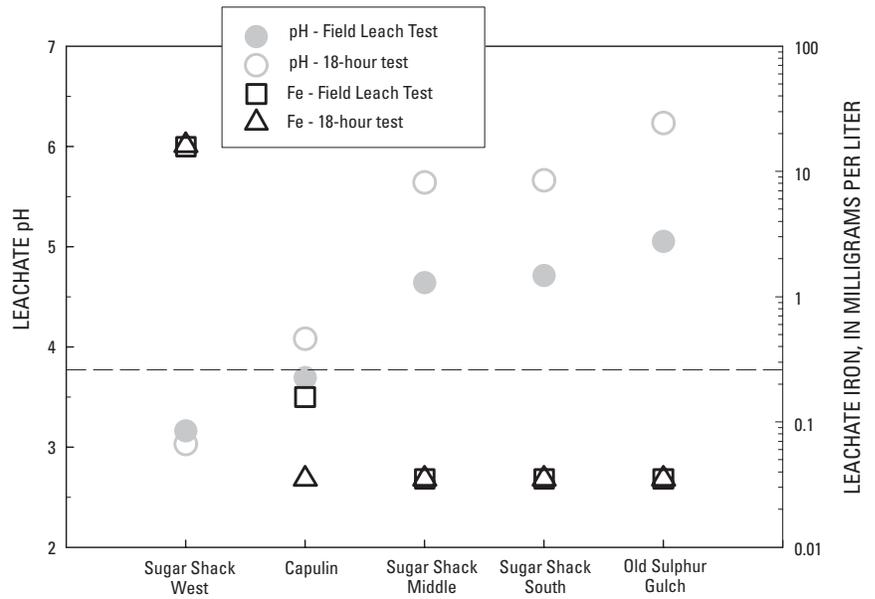


Figure 16. Leachate iron (Fe) concentration and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited mine waste-rock pile samples from the Questa Mine, New Mexico.

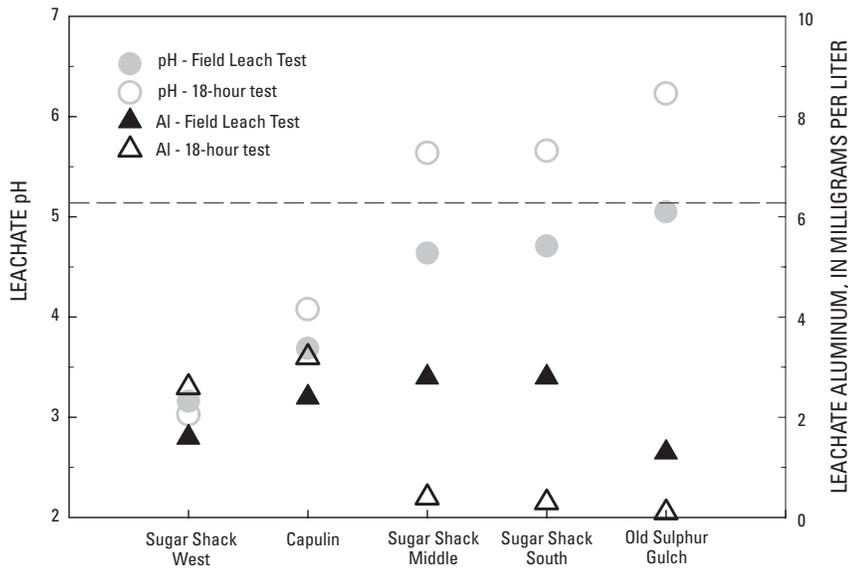
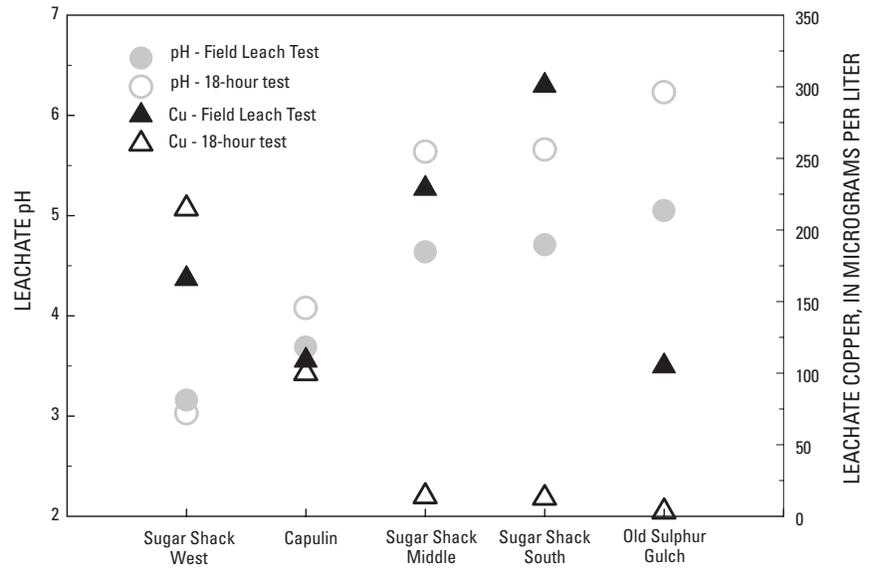


Figure 17. Leachate aluminum (Al) concentration and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited mine waste-rock pile samples from the Questa Mine, New Mexico.

Figure 18. Leachate copper (Cu) concentration and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited mine waste-rock pile samples from the Questa Mine, New Mexico.



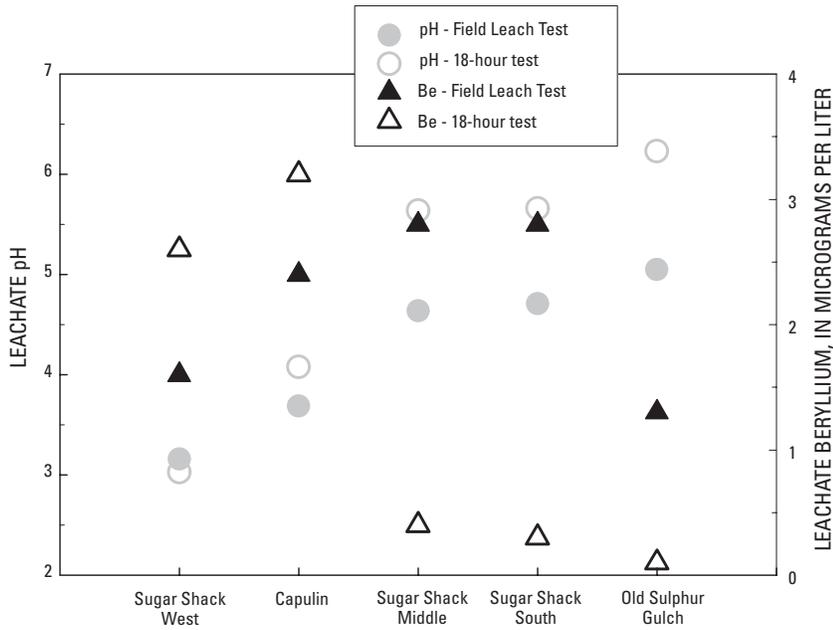
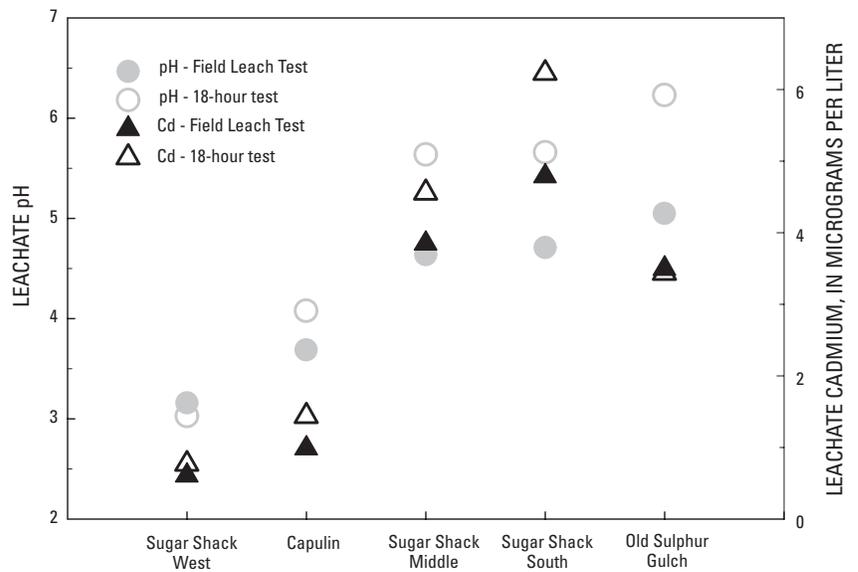


Figure 19. Leachate beryllium (Be) concentration and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited mine waste-rock pile samples from the Questa Mine, New Mexico.

Figure 20. Leachate cadmium (Cd) concentration and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited mine waste-rock pile samples from the Questa Mine, New Mexico.



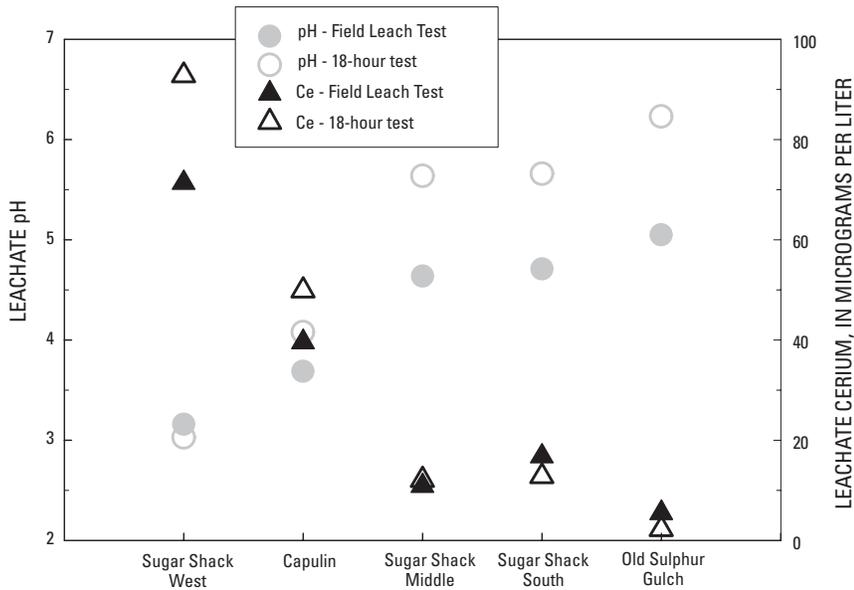
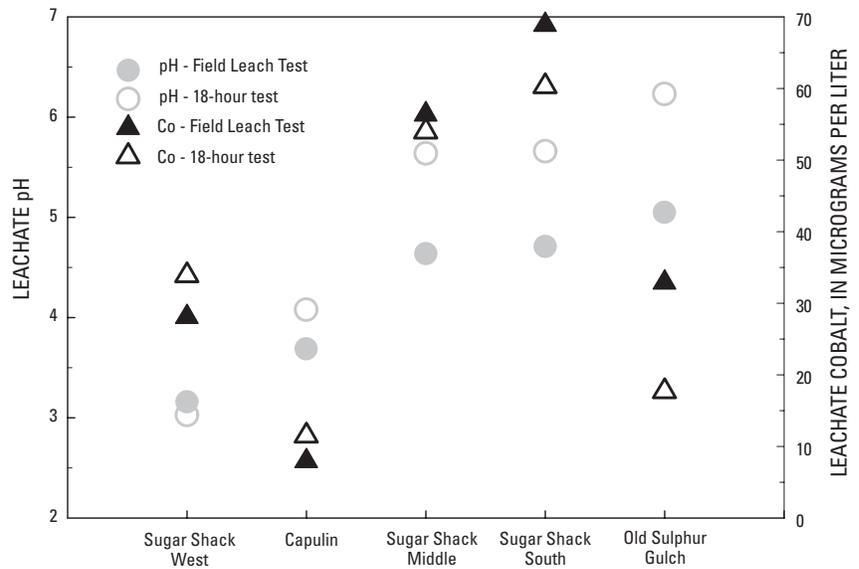


Figure 21. Leachate cerium (Ce) concentration and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited mine waste-rock pile samples from the Questa Mine, New Mexico.

Figure 22. Leachate cobalt (Co) concentration and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited mine waste-rock pile samples from the Questa Mine, New Mexico.



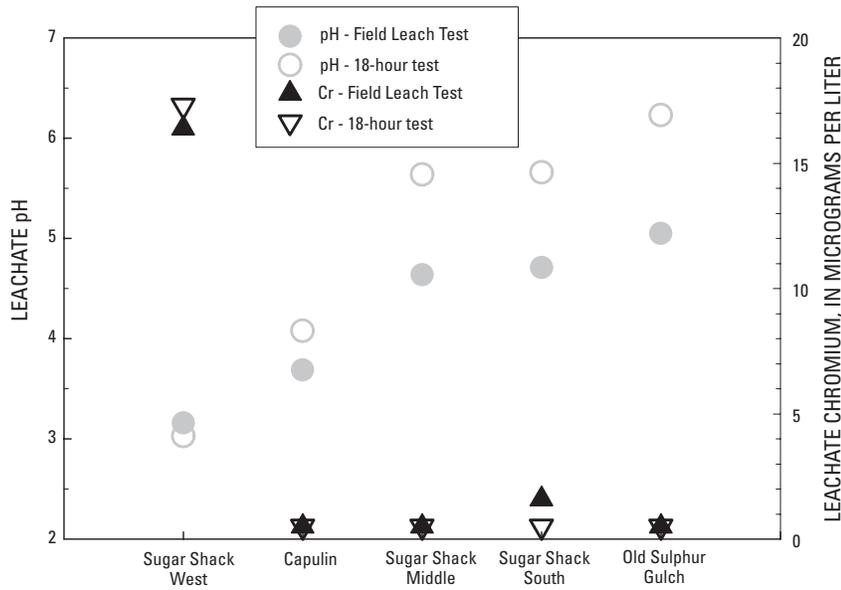
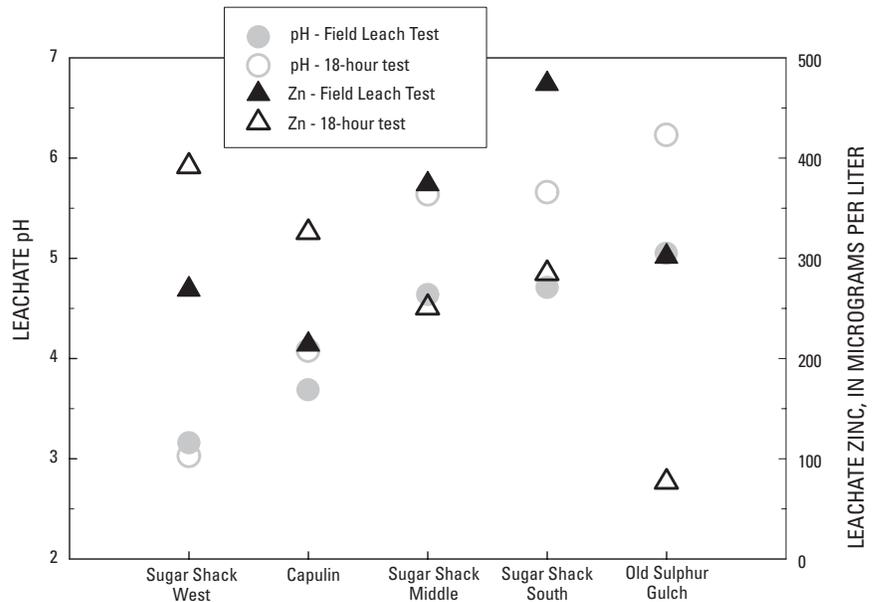


Figure 23. Leachate chromium (Cr) concentration and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited mine waste-rock pile samples from the Questa Mine, New Mexico.

Figure 24. Leachate zinc (Zn) concentration and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited mine waste-rock pile samples from the Questa Mine, New Mexico.



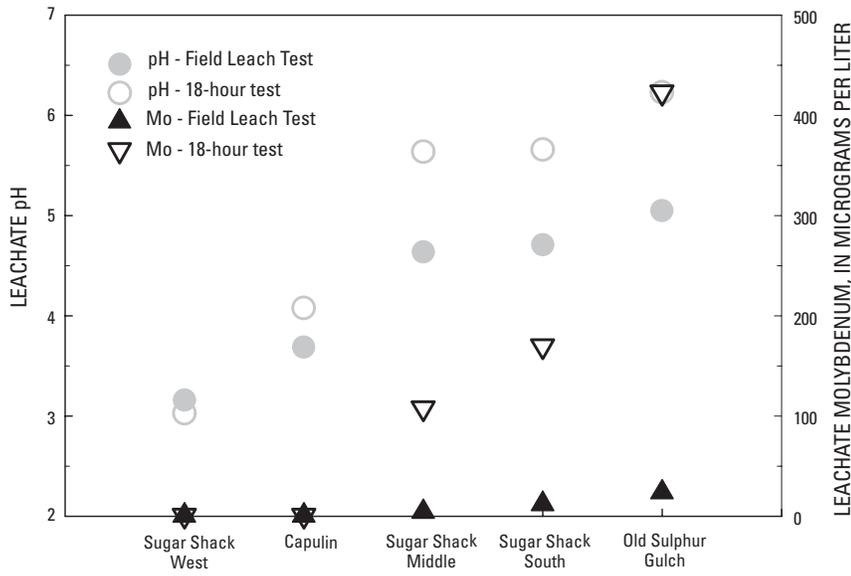
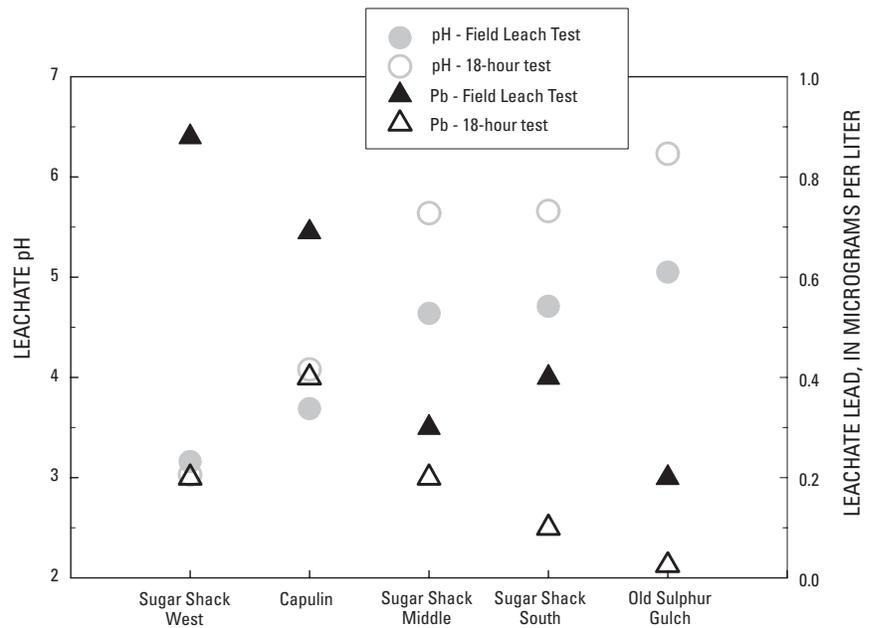


Figure 25. Leachate molybdenum (Mo) concentration and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited mine waste-rock pile samples from the Questa Mine, New Mexico.

Figure 26. Leachate lead (Pb) concentration and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited mine waste-rock pile samples from the Questa Mine, New Mexico.



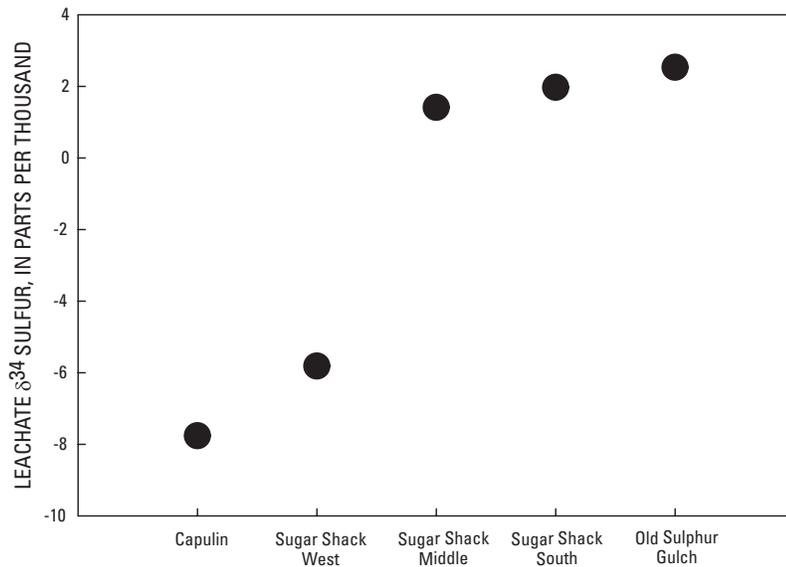


Figure 27. Isotopic composition of leachate sulfate (SO_4) from the mine waste-rock piles 18-hour leaching procedure for composited mine waste-rock pile samples from the Questa Mine, New Mexico.

per thousand), and June Bug (-3.4 to -4.1 parts per thousand) Creeks, and Verplanck and others (2006) measured the isotopic composition of sulfate from water in Goat Hill (-8.7 parts per thousand), Hansen (-6.9 to -8.6 parts per thousand), and Straight (-3.2 to -6.6 parts per thousand) Creeks. These $\delta^{34}\text{S}$ values are similar to our $\delta^{34}\text{S}$ values for the Sugar Shack West and Capulin leachates (-5.8 to -7.9 parts per thousand, respectively). Hence, the $\delta^{34}\text{S}$ values for the Sugar Shack West and Capulin leachates are more similar to the erosional scars than are the $\delta^{34}\text{S}$ values for the Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South leachates.

As was discussed in the “Sampling Strategy” section of this report, the waste-rock multi-increment samples were collected on two different collection trips, under different weather conditions, and by different samplers because of inclement weather during the first sampling trip. It is not known what effect this sampling difference has on the data. However, it is not likely that such sampling differences are responsible for the large differences in mineralogical, bulk-chemistry, and sulfur-isotope data discussed earlier in this report. Instead, it is likely that there are indeed differences in source material between the Capulin and Sugar Shack West piles compared to the Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South piles and that the Capulin and Sugar Shack West piles received material extracted near the top of the system. This depiction is consistent with the knowledge that the Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South piles are younger than the Capulin and Sugar Shack West piles.

Erosional Scar Leaching Results

The erosional-scar material has not been subjected to disturbance by mining and, as a result, should be more homogeneous than the waste-rock material for a given sample. Table 5 lists chemical analyses for leachates from the erosional scars. The pH of the erosional-scar leachates varies between 3.2 and 4.1, a much narrower range than for the mine waste-rock leachates. Figure 28 shows the pH values for the erosional-scar leachates for both the FLT and the 18-hour leaching procedure. Unlike the mine waste-rock leachates, the erosional-scar leachates exhibit little difference in their pH values between the two leaching procedures. Because the pH values are lower and more consistent for the erosional-scar leachates, the types of pH controls discussed previously for the waste-rock leachates generally do not apply. Figure 29 shows the specific conductance and sulfate concentrations for the erosional-scar leachates for the two leaching procedures. There is an increase in the specific conductance and sulfate concentrations between the FLT and the 18-hour leaching-procedure results. There is also an increase in calcium concentration between the FLT and the 18-hour procedure (table 5), indicating dissolution of gypsum with increased time and agitation. Assuming stoichiometric dissolution, calculations indicate that nearly all of the sulfate in most of the erosional scars can be explained by gypsum dissolution. Exceptions are the Goat Hill West and Hottentot scar samples for which only 24 percent and 35 percent, respectively, of the leachate sulfate can be attributed

Table 5. Leachate chemical analyses for composited erosional-scar samples, Questa, New Mexico.

[Analyzed by ICP-MS unless otherwise noted; —, not determined; Sp. Cond., specific conductance; $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $\mu\text{g}/\text{L}$, micrograms per liter; mg/L , milligrams per liter; <, less than; ‰, parts per thousand]

Property or constituent ¹	Geometric mean ²	18-hour test									
		Goat Hill West	Goat Hill	Sulphur Gulch	SW Hansen Creek	Hansen Creek	Straight Creek	SE Straight Creek	Hottentot Creek	June Bug	Less-altered site ³
pH	—	3.7	3.8	3.6	3.2	4.1	3.3	3.8	3.3	4.0	7.1
Sp. Cond. $\mu\text{S}/\text{cm}$	—	603	401	1,530	1,930	1,210	1,270	817	379	922	142
Ag $\mu\text{g}/\text{L}$	—	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3
Al* mg/L	6.5	30	3.0	37	22	11	11	5.1	4.2	4.2	1.8
As $\mu\text{g}/\text{L}$	—	2	<1	<1	<1	<1	<1	<1	<1	<1	1
Ba $\mu\text{g}/\text{L}$	49.9	60.3	45.9	35.4	40.6	44.4	42.4	59	64.3	48.1	122
Be $\mu\text{g}/\text{L}$	1.7	5.1	1.3	6.3	4.2	6.2	3.2	1.4	.90	2.6	.050
Bi $\mu\text{g}/\text{L}$	—	—	.02	0.006	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	.02
Ca* mg/L	102	38.0	54.0	322	406	268	234	162	8.90	207	21.0
Cd $\mu\text{g}/\text{L}$	1.3	5.9	1.1	3.1	1.4	2.4	4.4	2.1	1.7	2.2	.050
Ce $\mu\text{g}/\text{L}$	14	15	4.1	45	58	29	62	8.8	3.9	58	1.2
Co $\mu\text{g}/\text{L}$	22	76	11	110	69	73	37	18	15	24	1.3
Cr $\mu\text{g}/\text{L}$	5.0	9.4	<1	8.9	11	<1	5.9	<1	3.1	<1	1.2
Cs $\mu\text{g}/\text{L}$	.054	.12	.020	.050	.040	.040	.080	.040	.10	.040	.13
Cu $\mu\text{g}/\text{L}$	118	630	129	688	121	79.0	303	61.9	114	313	9.9
Fe* mg/L	.58	.28	.13	.32	6.0	.28	3.3	.24	2.0	.073	.84
Ga $\mu\text{g}/\text{L}$	.23	.56	.06	.58	.68	.33	.60	.10	.07	.40	.24
Ge $\mu\text{g}/\text{L}$	.08	.20	.03	.22	.20	.10	.20	.04	.02	.10	< 0.02
K mg/L	1.8	1.5	2.0	1.1	0.85	2.3	1.9	2.1	2.0	2.7	5.6
La $\mu\text{g}/\text{L}$	4.2	3.1	1.2	9.9	16	6.3	18	2.7	1.2	24	.61
Li $\mu\text{g}/\text{L}$	7.9	27	4.0	46	20	11	13	4.3	4.0	12	1.7
Mg* mg/L	7.1	19	2.8	26	29	18	8.4	4.7	3.5	3.5	3.7
Mn* mg/L	.94	4.0	1.2	3.0	2.2	4.5	1.8	1.2	.48	1.1	.022
Mo $\mu\text{g}/\text{L}$	.74	< 2	.49	.30	.35	< 0.2	.23	< 0.2	< 0.2	< 0.2	16
Na mg/L	.58	1.2	.70	.72	.42	.39	.54	.47	.30	.39	4.1
Nb $\mu\text{g}/\text{L}$	.037	< 0.02	.040	.040	.040	.020	.020	< 0.02	< 0.02	< 0.02	.10
Ni $\mu\text{g}/\text{L}$	51.8	194	21.0	234	162	164	82.6	40.4	32.7	45.9	5.90
P mg/L	.04	.09	< 0.01	.03	.03	< 0.01	.01	< 0.01	< 0.01	< 0.01	.4

Table 5. Leachate chemical analyses for composited erosional-scar samples, Questa, New Mexico.—Continued

[Analyzed by ICP-MS unless otherwise noted; —, not determined; Sp. Cond., specific conductance; $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $\mu\text{g}/\text{L}$, micrograms per liter; mg/L , milligrams per liter; <, less than; ‰, parts per thousand]

Property or constituent ¹	Geometric mean ²	18-hour test									
		Goat Hill West	Goat Hill	Sulphur Gulch	SW Hansen Creek	Hansen Creek	Straight Creek	SE Straight Creek	Hottentot Creek	June Bug	Less-altered site ³
Pb $\mu\text{g}/\text{L}$	.3	<0.05	.2	<0.05	.4	.2	.4	.1	.07	1	1
Rb $\mu\text{g}/\text{L}$	2.9	13	3.9	4.6	1.8	3.3	4.1	2.7	3.9	2.5	1.4
Sb $\mu\text{g}/\text{L}$	.3	.4	.3	.2	.2	.2	.6	.2	.2	.1	9
Sc $\mu\text{g}/\text{L}$	.7	.6	.4	1	3	.8	2	.5	.4	.6	.5
Se $\mu\text{g}/\text{L}$	1.7	1.5	< 1	2.4	1.7	1.3	1.6	1.2	< 1	2.6	< 1
Si mg/L	1.4	1.0	1.0	1.2	1.3	1.5	1.3	1.4	1.0	1.6	2.8
SO ₄ mg/L	278	—	151	903	1,090	657	615	383	80.0	460	22.0
Sr $\mu\text{g}/\text{L}$	164	14.2	35.8	576	1,780	500	84.5	89.2	15.2	1160	116
Ta $\mu\text{g}/\text{L}$	.03	—	< 0.02	.03	.03	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
Th $\mu\text{g}/\text{L}$	.13	< 0.2	.10	.12	1.5	.02	1.5	.05	.10	.03	.14
Ti $\mu\text{g}/\text{L}$	4.9	3.9	1.8	11	13	7.4	7.0	4.4	1.0	5.0	9.6
Tl $\mu\text{g}/\text{L}$	.07	<0.1	.07	.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
U $\mu\text{g}/\text{L}$	1.2	24	.83	3.5	3.7	1.8	3.1	.56	1.7	1.3	.08
V $\mu\text{g}/\text{L}$	.5	<0.5	<0.1	<0.1	.2	<0.1	<0.1	<0.1	<0.1	<0.1	2
W $\mu\text{g}/\text{L}$	.04	—	.06	.09	.04	.04	.04	.02	< 0.02	.02	.10
Y $\mu\text{g}/\text{L}$	8.7	31	3.3	52	39	23	21	5.9	3.5	15	.59
Zn $\mu\text{g}/\text{L}$	222	1,750	235	331	295	522	634	195	200	185	31.7
Zr $\mu\text{g}/\text{L}$	—	< 0.2	.20	< 0.05	< 0.05	< 0.05	< 0.05	.07	< 0.05	< 0.05	1.8
$\delta^{34}\text{S}$ ‰	—	-2.1	—	—	—	—	—	—	—	—	—
F** mg/L	—	.80	.72	1.2	.81	.78	.92	.54	.14	.84	—
Cl** mg/L	—	<0.6	.69	.76	.80	<0.6	<0.6	<0.6	<0.6	.51	—
SO ₄ ** mg/L	—	340	170	1,000	1,260	500	690	430	93.0	518	—

Table 5. Leachate chemical analyses for composited erosional-scar samples, Questa, New Mexico.—Continued

[Analyzed by ICP-MS unless otherwise noted; —, not determined; Sp. Cond., specific conductance; $\mu\text{S/cm}$, microsiemens per centimeter; $\mu\text{g/L}$, micrograms per liter; mg/L , milligrams per liter; <, less than; ‰, parts per thousand]

Property or constituent ¹	Geometric mean ²	Field Leach Test									
		Goat Hill West	Goat Hill	Sulphur Gulch	SW Hansen Creek	Hansen Creek	Straight Creek	SE Straight Creek	Hottentot Creek	June Bug	Less-altered site ³
pH	—	3.7	3.7	3.6	3.2	3.8	3.3	3.7	3.3	3.8	6.8
Sp. Cond. $\mu\text{S/cm}$	—	547	251	993	1,060	743	642	400	324	446	67
Ag $\mu\text{g/L}$	—	<3	<3	<3	<3	<3	<3	<3	<3	<3	<3
Al* mg/L	2.9	21	1.2	24	9.3	5.9	3.5	1.2	2.2	.94	.97
As $\mu\text{g/L}$	—	<1	<1	<1	<1	<1	<1	<1	<1	<1	<1
Ba $\mu\text{g/L}$	35	83	47	32	9.3	8.7	44	93	23	41	160
Be $\mu\text{g/L}$	1.9	3.1	1.0	5.3	3.1	5.6	2.1	0.90	0.60	1.6	<0.05
Bi $\mu\text{g/L}$	.02	—	.03	.01	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	< 0.005	.02
Ca* mg/L	46.1	34.0	24.0	144	144	128	79.0	52.0	6.00	75.0	8.00
Cd $\mu\text{g/L}$	.91	4.5	.72	2.5	1.0	1.8	2.8	1.2	1.2	1.2	.030
Ce $\mu\text{g/L}$	6.2	10	1.4	28	25	15	19	1.9	2.3	13	0.79
Co $\mu\text{g/L}$	14	58	6.8	89	53	46	22	9.6	11	8.7	0.67
Cr $\mu\text{g/L}$	7.5	14	<1	16	11	<1	3.8	<1	4.7	<1	<1
Cs $\mu\text{g/L}$	.076	.14	.020	.070	.090	.080	.12	.070	.19	.060	.090
Cu $\mu\text{g/L}$	92.6	503	99.5	625	102	78.9	202	45.2	93.2	213	5.5
Fe* mg/L	.60	.40	.27	.31	3.8	.82	1.7	.31	1.8	.10	.38
Ga $\mu\text{g/L}$	.12	.41	.03	.40	.41	.20	.21	.02	.05	.09	.20
Ge $\mu\text{g/L}$	.05	.20	< 0.02	.10	.06	.06	.03	< 0.02	< 0.02	.02	< 0.02
K mg/L	.80	.73	.71	.50	.20	1.2	.61	1.1	.73	1.0	3.4
La $\mu\text{g/L}$	1.8	1.6	.34	5.6	6.7	3.1	5.3	.52	.64	5.4	.42
Li $\mu\text{g/L}$	5.9	19	3.3	39	18	6.7	9.7	3.3	3.0	4.6	1.2
Mg* mg/L	4.8	16	1.9	21	22	14	5.7	2.7	2.6	2.1	1.4
Mn* mg/L	.59	2.9	.66	2.4	1.6	2.8	1.1	.58	.33	.44	.014
Mo $\mu\text{g/L}$	.87	< 2	1.2	.36	.34	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	4.0
Na mg/L	.40	1.3	.63	.53	.14	.18	.54	.70	.070	.34	3.6
Nb $\mu\text{g/L}$	.039	< 0.02	.050	.040	.030	.030	.020	< 0.02	< 0.02	< 0.02	.10
Ni $\mu\text{g/L}$	36.2	156	13.7	198	131	124	51.5	23.5	24.4	24.6	3.30
P mg/L	.03	.09	.01	.04	.02	.01	< 0.01	.02	< 0.01	< 0.01	.4
Pb $\mu\text{g/L}$	.4	.1	.1	< 0.05	.9	.5	.8	.2	.2	1	.4

Table 5. Leachate chemical analyses for composited erosional-scar samples, Questa, New Mexico.—Continued

[Analyzed by ICP-MS unless otherwise noted; —, not determined; Sp. Cond., specific conductance; $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $\mu\text{g}/\text{L}$, micrograms per liter; mg/L , milligrams per liter; <, less than; ‰, parts per thousand]

Property or constituent ¹	Geometric mean ²	Field Leach Test									
		Goat Hill West	Goat Hill	Sulphur Gulch	SW Hansen Creek	Hansen Creek	Straight Creek	SE Straight Creek	Hottentot Creek	June Bug	Less-altered site ³
Rb $\mu\text{g}/\text{L}$	2.8	11	2.9	4.8	2.1	4.3	3.8	2.8	3.6	2.2	.88
Sb $\mu\text{g}/\text{L}$	.3	.8	.4	.2	.2	.2	.6	.5	.2	.2	2
Sc $\mu\text{g}/\text{L}$	.4	< 0.6	< 0.1	.9	2	.5	.6	.2	< 0.1	.2	.2
Se $\mu\text{g}/\text{L}$	1.6	< 1	< 1	1.6	< 1	< 1	< 1	< 1	< 1	< 1	< 1
Si mg/L	—	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	< 0.2	1.2
SO ₄ mg/L	147	—	77.0	509	482	350	213	138	60.0	167	16.0
Sr $\mu\text{g}/\text{L}$	48.9	6.57	10.2	84.0	250	204	20.2	26.1	5.8	271	44.4
Ta $\mu\text{g}/\text{L}$	.02	—	< 0.02	.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02	< 0.02
Th $\mu\text{g}/\text{L}$	.12	.24	.10	.16	1.2	.04	.68	.05	.13	.02	.09
Ti $\mu\text{g}/\text{L}$	2.7	3.0	1.0	6.7	6.7	4.0	2.7	1.8	1.0	1.9	4.7
Tl $\mu\text{g}/\text{L}$	.10	< 0.1	.20	.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05	< 0.05
U $\mu\text{g}/\text{L}$	.87	28	.72	3.6	2.5	2.1	1.6	.34	1.4	.73	.04
V $\mu\text{g}/\text{L}$	.3	< 0.5	< 0.1	< 0.1	.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	1
W $\mu\text{g}/\text{L}$	.05	—	.07	.09	.04	.04	.03	< 0.02	< 0.02	< 0.02	.08
Y $\mu\text{g}/\text{L}$	4.0	25	1.2	35	18	11	6.3	1.3	2.2	3.2	.56
Zn $\mu\text{g}/\text{L}$	171	1,250	181	290	241	406	462	155	134	122	20.4
Zr $\mu\text{g}/\text{L}$	—	< 0.2	.20	< 0.05	< 0.05	< 0.05	< 0.05	.08	< 0.05	< 0.05	.90
$\delta^{34}\text{S}$ ‰	—	—	—	—	—	—	—	—	—	—	—
F** mg/L	—	.69	.30	1.4	1.4	.52	.61	.15	.09	< 0.05	.32
Cl** mg/L	—	< 0.6	< 0.6	.57	1.2	1.2	< 0.6	< 0.6	1.2	< 0.6	1.1
SO ₄ ** mg/L	—	300	84.0	584	530	380	240	160	73.0	200	20.0

¹ Constituents marked with an asterisk were analyzed by ICP–AES. Constituents marked with two asterisks were analyzed by IC. The pH, specific conductance, and sulfur isotope analytical methods are described in the text.

² Does not include the less-altered site.

³ Less-altered drainage west of SW Hansen Creek.

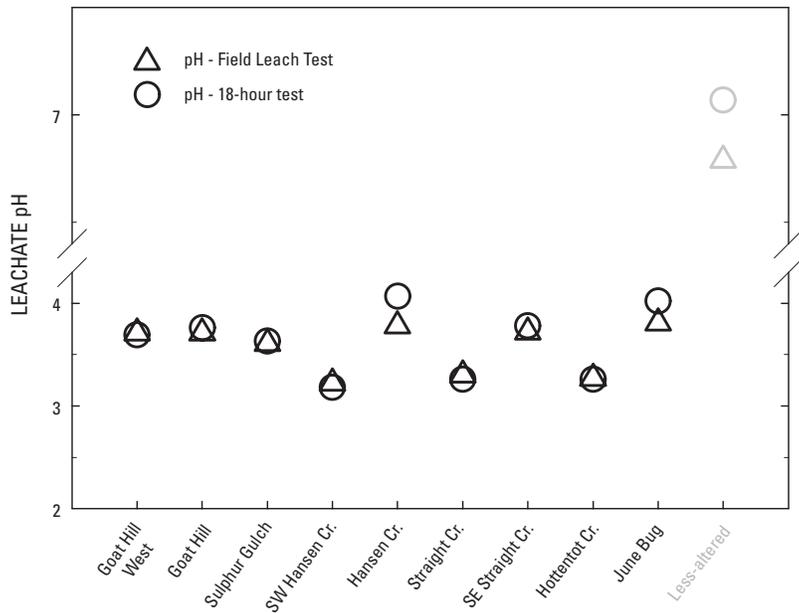


Figure 28. Leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited erosional-scar samples and a less-altered sample near Questa, New Mexico. Cr., Creek.

to gypsum dissolution. The Hansen Creek sample appears to have substantial calcite dissolution in addition to gypsum dissolution with increasing time and agitation during the leaching tests.

The elemental content of the erosional-scar leachates is highly variable between scars, which results in a large range of values for several elements. Figure 30 shows the iron concentrations and figure 31 shows the aluminum concentrations for the two leaching procedures. With the exception of the Southwest Hansen Creek scar leachate, the iron concentrations are similar between the two leaching procedures. The leachate pH measurements are around the pH 3.7 solubility control pH for schwertmannite or other sulfate-substituted hydrous ferric oxides previously described for the waste-rock leachates; hence, iron concentrations may be at least partially controlled by pH-dependent solubility reactions. For aluminum, the 18-hour leachates always exhibited higher concentrations than the FLT leachates, and all are within or less than a factor of about two for a given sample. All the leachate pH measurements are below the pH 5.1 solubility control pH for aluminum, so there does not appear to be any aluminum solubility control in the scar leachates.

Comparison of Waste-Rock and Erosional-Scar Leaching Results

Figures 32 and 33 show box plots for 18-hour leachates from the mine waste-rock piles and the erosional scars (for preparation of graphs, data points with qualified values were replaced with a value equal to 50 percent of the detection

limit). When the elemental concentrations in the waste-rock leachates are compared with concentrations in the scar leachates, generally the waste-rock leachates do not exceed the upper range of the erosional-scar leachates. One exception is molybdenum, which is notably higher in the waste-rock leachates than in the scar leachates. Another exception is iron, where the elevated concentration of iron in the Sugar Shack West leachate is anomalous. The data shown in figures 28, 32, and 33 indicate that the erosional-scar areas can contribute low-pH waters with elevated metal concentrations. Because of the low pH of the scar leachates (pH <4.1), many metals can be mobilized and remain in solution, the exception being anionic species such as molybdenum, which tend to be less mobile under acidic conditions. The source material for the Capulin and Sugar Shack West waste-rock piles appears to be similar to the source material for the scar areas. The leachate pH values for the Capulin (pH 3.7 and 4.1) and Sugar Shack West (pH 3.2 and 3.0) waste-rock piles are in the same range as those of the erosional scars.

Table 6 gives a comparison of the geometric means for leachate chemistry of the mine waste-rock piles with the leachate chemistry of the Straight Creek scar area. Most crucial to understanding the differences in leachate chemistry is the difference in leachate pH values. The pH of the Straight Creek leachate is 3.3. This pH is low enough to maintain iron and aluminum in solution, which in turn allows for greater mobility of many cationic species in the leachate. Elements in higher concentration in the Straight Creek leachate include Al, Be, Ce, Cu, La, Pb, U, Y, and Zn. Elements generally in higher concentration in the waste-rock leachates include Ba, Mn, Na, and Sr.

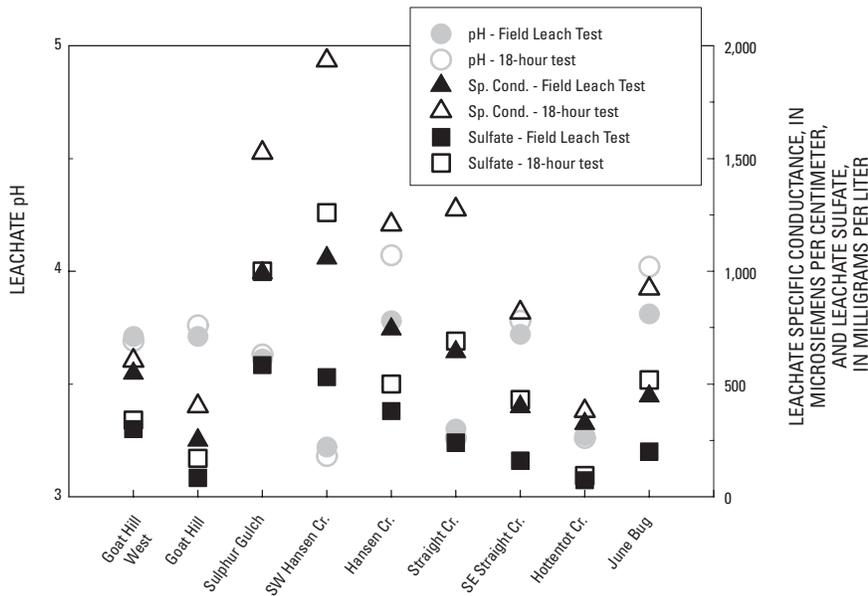
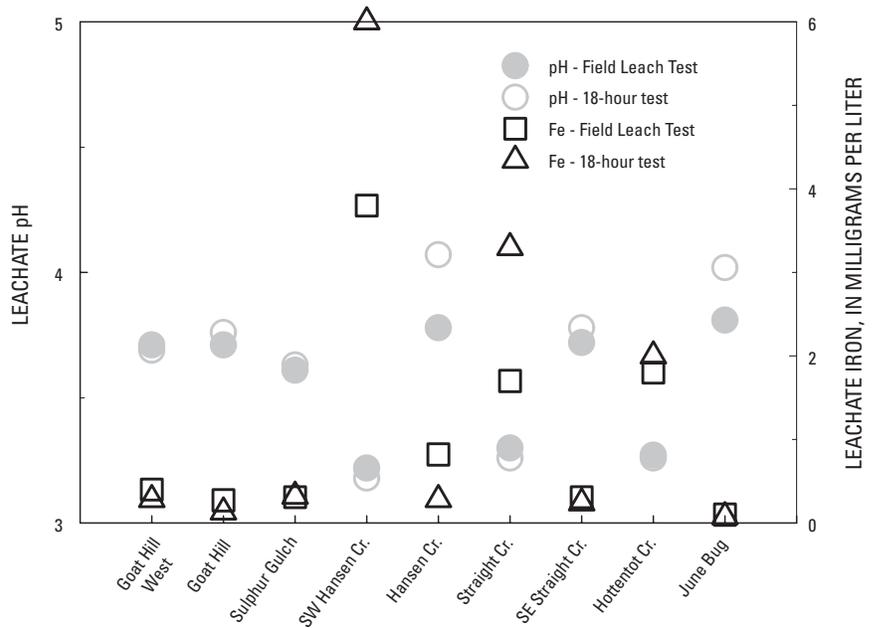


Figure 29. Leachate specific conductance, leachate sulfate concentration, and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited erosional-scar samples near Questa, New Mexico. Cr., Creek; Sp. Cond., specific conductance.

Figure 30. Leachate iron (Fe) concentration and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited erosional-scar samples near Questa, New Mexico. Cr., Creek.



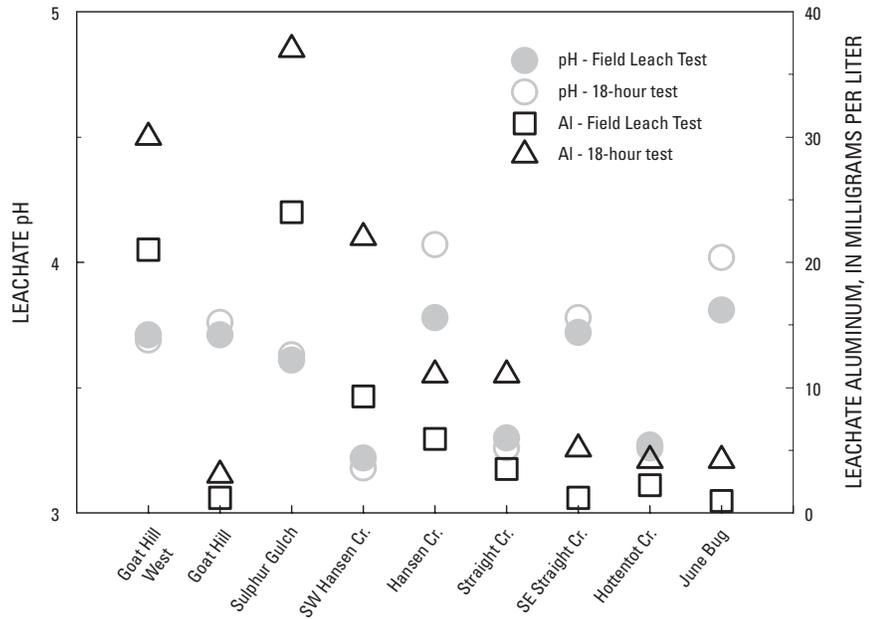


Figure 31. Leachate aluminum (Al) concentration and leachate pH from the Field Leach Test (FLT) and the 18-hour leaching procedure for composited erosional-scar samples near Questa, New Mexico. Cr., Creek.

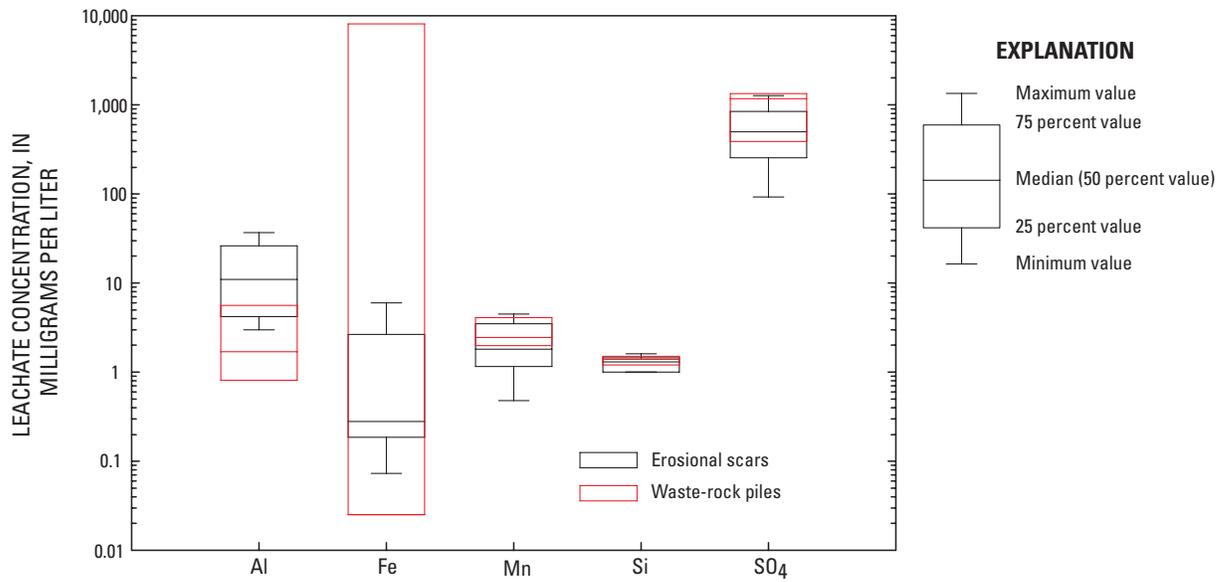


Figure 32. Box plots for selected leachable major-element concentrations from the 18-hour leaching procedure for composited erosional-scar samples near Questa, New Mexico, and composited mine waste-rock pile samples from the Questa Mine, New Mexico.

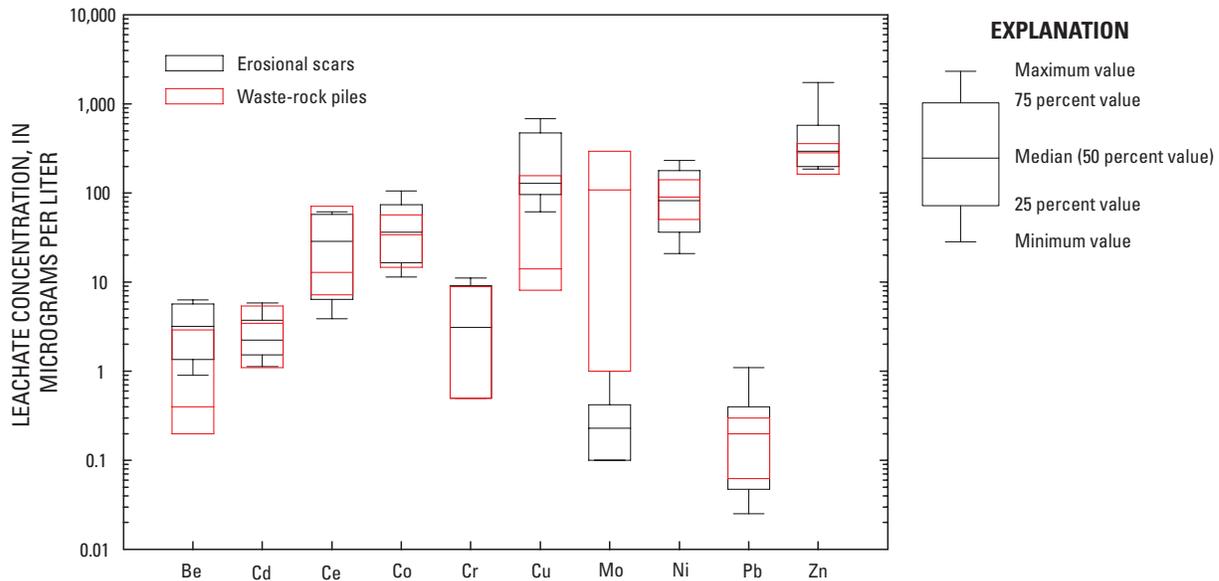


Figure 33. Box plots for selected leachable minor- and trace-element concentrations from the 18-hour leaching procedure for composited erosional-scar samples near Questa, New Mexico, and composited mine waste-rock pile samples from the Questa Mine, New Mexico.

Comparison of Leachate Composition with Scar-Drainage Waters

Figures 34 and 35 provide a comparison of the composition of the FLT (filled triangles) and 18-hour leachates (open triangles) with surface waters, stormwater runoff, and snowmelt runoff from Straight Creek (for preparation of graphs, data points with qualified values were replaced with a value equal to 50 percent of the detection limit). The box plots represent 10 filtered surface-water samples from Straight Creek collected at intervals between October 2000 and October 2003 (data from Verplanck and others, 2006; samples 00WA197, 02WA121, 02WA124, 02N287, 02N288, 03WA101, 03WA115, 03N072, 03N122, 03WA165). The diamonds are data from a storm event in September 2002, which was the largest storm event of the season; the filled diamonds are filtered runoff collected on the first day of the storm (sample 02WA154), and the open diamonds are filtered runoff collected on day 3 (sample 02WA158), still during a time of heavy runoff (data from Verplanck and others, 2006). The inverted triangles are data from a runoff sample taken a day after a spring snowmelt event in 2003 (data from Verplanck and others, 2006; sample 03WA110). The pH values of the FLT and 18-hour leachates for Straight Creek were both 3.3, the drainage waters ranged from pH 2.7 to 3.1, the stormwater runoff samples were pH 3.0 for day 1 and 2.8 for day 3, and the snowmelt runoff sample was pH 2.9. With the exception of molybdenum and lead, the compositions of the natural drainage waters and runoff waters are quite comparable

(figs. 34 and 35). The FLT and 18-hour leachates have substantially lower element concentrations than do the natural Straight Creek waters, but the overall trends (that is, signatures or fingerprints) between elements are similar. Analogous findings were reported for comparison of the FLT with mine-waste seep compositions at the Rattler mine site in Colorado (Hageman and others, 2005). Comparison of these data reinforce the earlier statement that these (or any) leaching procedures cannot provide quantitative concentrations of actual waste-rock or scar contributions to surface or ground water. However, they can provide qualitative information about the likely chemical composition of porewater within the waste-rock piles and erosional scars.

Figure 36 shows calcium concentrations plotted against sulfate concentrations for leachates, Straight Creek surface-water samples (data from Verplanck and others, 2006; samples 00WA197, 02WA121, 02WA124, 02N287, 02N288, 03WA101, 03WA115, 03N072, 03N122, 03WA165), and additional erosional-scar filtered surface-water samples collected from the Capulin, Waldo Springs (not shown in fig. 1), Southwest Hansen, west of Southwest Hansen, Hansen, June Bug, and Hottentot scar areas (data from Verplanck and others, 2006; samples 04WA102, 04WA103, 01WA163, 01WA162, 01WA153, 01WA152, 01WA151, 01WA161, 01WA160, 01WA157, 01WA156). Dissolved calcium concentrations are derived from gypsum dissolution with additional calcite dissolution for some sites. Dissolved sulfate concentrations originate from gypsum dissolution or byproducts from pyrite oxidation. Both the waste-rock pile leachates and the erosional-scar leachates exhibit a fairly tight trend and have

Table 6. Comparison of the geometric means of leachate chemical analyses for composited mine waste-rock pile material with the leachate chemical analysis of the Straight Creek erosional-scar area, Questa, New Mexico.

[—, not determined; Sp. Cond., specific conductance; $\mu\text{S}/\text{cm}$, microsiemens per centimeter; $\mu\text{g}/\text{L}$, micrograms per liter; mg/L , milligrams per liter; <, less than]

Property or constituent	Geometric mean of mine waste-rock piles ¹	Straight Creek ²	Ratio
pH	4.9	3.3	1.5
Sp. Cond. $\mu\text{S}/\text{cm}$	1,470	1,270	1.2
Ag $\mu\text{g}/\text{L}$	—	<3	—
Al mg/L	1.4	11	.13
As $\mu\text{g}/\text{L}$	—	<1	—
Ba $\mu\text{g}/\text{L}$	70	42	1.6
Be $\mu\text{g}/\text{L}$	.63	3.2	.20
Ca mg/L	280	230	1.2
Cd $\mu\text{g}/\text{L}$	2.6	4.4	.58
Ce $\mu\text{g}/\text{L}$	17	62	.28
Co $\mu\text{g}/\text{L}$	30	37	.81
Cr $\mu\text{g}/\text{L}$	—	5.9	—
Cs $\mu\text{g}/\text{L}$	—	.08	—
Cu $\mu\text{g}/\text{L}$	27	300	.088
Fe $\mu\text{g}/\text{L}$	—	3,300	—
Ga $\mu\text{g}/\text{L}$	.31	.60	.52
Ge $\mu\text{g}/\text{L}$	.10	.20	.52
K mg/L	2.5	1.9	1.3
La $\mu\text{g}/\text{L}$	8.2	18	.46
Li $\mu\text{g}/\text{L}$	15	13	1.2
Mg mg/L	11	8.4	1.3
Mn $\mu\text{g}/\text{L}$	2,740	1,800	1.5
Mo $\mu\text{g}/\text{L}$	—	.23	—
Na mg/L	1.3	.54	2.4
Nb $\mu\text{g}/\text{L}$	—	.02	—
Ni $\mu\text{g}/\text{L}$	83	83	1.0
P mg/L	—	.01	—
Pb $\mu\text{g}/\text{L}$	.20	.40	.50
Rb $\mu\text{g}/\text{L}$	4.9	4.1	1.2
Sb $\mu\text{g}/\text{L}$	.60	.62	.97
Sc $\mu\text{g}/\text{L}$	—	1.7	—
Se $\mu\text{g}/\text{L}$	—	1.6	—
Si mg/L	1.4	1.3	1.0
SO ₄ mg/L	715	615	1.2
Sr $\mu\text{g}/\text{L}$	930	85	11
Th $\mu\text{g}/\text{L}$	—	1.5	—
Ti $\mu\text{g}/\text{L}$	8.8	7.0	1.3
Tl $\mu\text{g}/\text{L}$	—	<0.05	—
U $\mu\text{g}/\text{L}$	.51	3.1	.16
V $\mu\text{g}/\text{L}$	—	<0.1	—
Y $\mu\text{g}/\text{L}$	7.5	21	.36
Zn $\mu\text{g}/\text{L}$	230	630	.37
Zr $\mu\text{g}/\text{L}$	—	< 0.05	—

¹ Geometric mean of five mine waste-rock piles listed in table 4 for the 18-hour leaching procedure.

² From values listed in table 5 for the 18-hour leaching procedure.

higher calcium-to-sulfate ratios than do the natural erosional-scar samples. Also, the natural erosional-scar data are much more scattered than the leachate data. It appears that either the leachates have a larger contribution of calcium from calcite than do the natural samples, or the natural samples have a larger contribution of pyrite-oxidation products, such as readily soluble sulfate salts. Calcium-to-sulfate ratios range from 0.3 to 0.4 for the waste-rock pile leachates and from 0.1 to 0.5 for the erosional-scar leachates.

Comparison with Previous Leaching Studies

Shaw and others (2002, 2003) used a solid-to-solution leach ratio of 1:3 in contrast to the 1:20 ratio used in this study. Consequently, quantitative comparison of leachate concentrations between the leaching studies is problematic. However, qualitative findings between the studies can be compared and generally are consistent. For example, Shaw and others (2003) reported on the contaminant loads from erosional scars and concluded that the erosional scars contribute significant concentrations of sulfate and leachable metals and that the composition and concentration of leachable metals vary significantly between scars and within a given scar. These conclusions generally are consistent with the findings of our study, although variation within a given scar was not addressed in our study because we chose to collect multi-increment samples to represent average geochemical behavior from a given site. Our study finds large variation in the composition and concentration of leachable metals between scar areas, and the pH of the scar leachates was consistently low (<pH 4.1).

Shaw and others (2002) found that the majority of the mine waste-rock material is acid generating and that oxidation of pyrite in the waste-rock piles has produced leachable oxidation products. They also found pH control on the concentrations of metals in the leachates. Our findings are consistent with Shaw and others (2002), but in addition to the acid-generating potential of most of the waste-rock material, our study observed pH increases with time and agitation in leachates from the waste-rock material. Also, our study observed pH-dependent concentrations of several metals in response to the changing pH conditions in the leachates.

Summary

This report documents the leaching characteristics of surficial samples of composited mine waste-rock material and of naturally altered areas. In the bulk <2-mm samples, quartz, mica (probably sericite), and X-ray

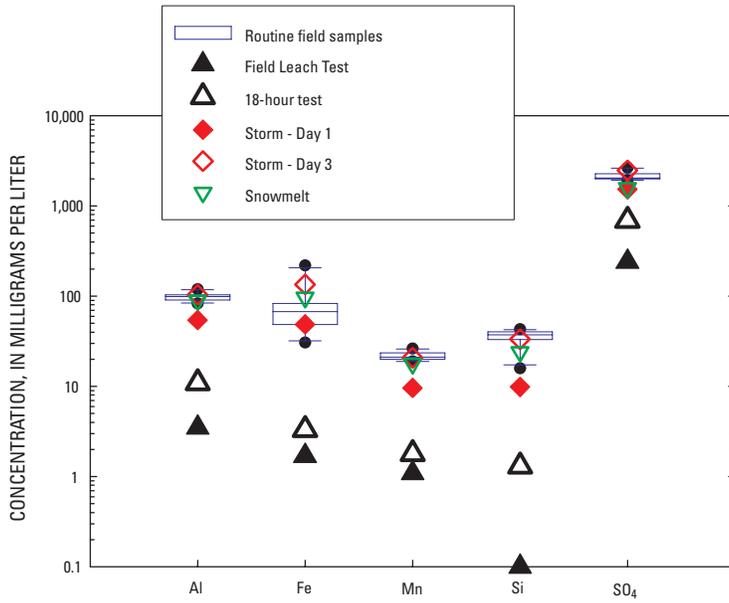
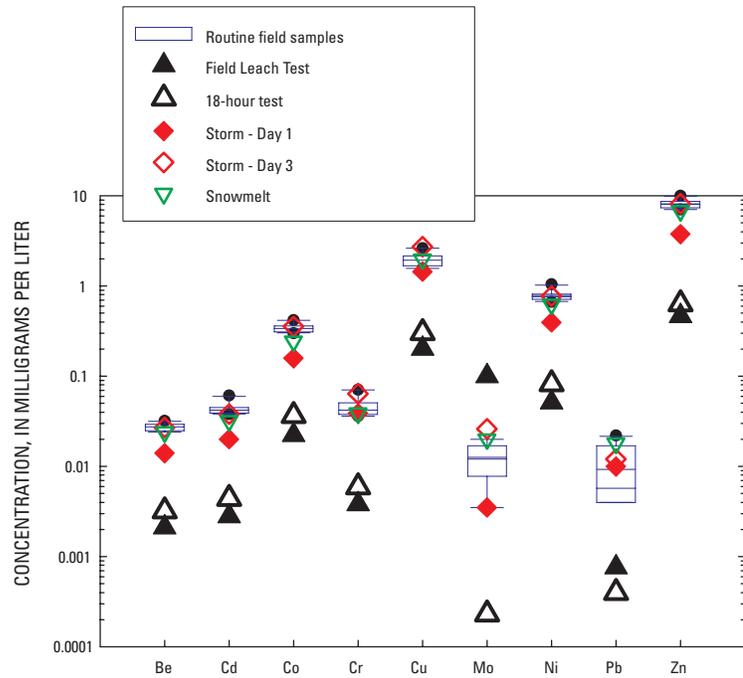


Figure 34. Comparison of the concentration of selected leachable major-element concentrations from leaching tests and surface-water samples collected from Straight Creek, near Questa, New Mexico. Field-sample data are from Verplanck and others (2006). Field Leach Test (FLT) data are shown as filled triangles, and 18-hour test data are shown as open triangles. Box plots represent 10 filtered drainage samples from Straight Creek collected at intervals between October 2000 and October 2003, diamonds are data from a storm event in September 2002, and inverted triangles are data from a runoff sample taken a day after a spring snowmelt event in 2003.

Figure 35. Comparison of the concentration of selected leachable minor- and trace-element concentrations from leaching tests and surface-water samples collected from Straight Creek, near Questa, New Mexico. Field-sample data are from Verplanck and others (2006). Field Leach Test (FLT) data are shown as filled triangles, and 18-hour test data are shown as open triangles. Box plots represent 10 filtered drainage samples from Straight Creek collected at intervals between October 2000 and October 2003, diamonds are data from a storm event in September 2002, and inverted triangles are data from a runoff sample taken a day after a spring snowmelt event in 2003.



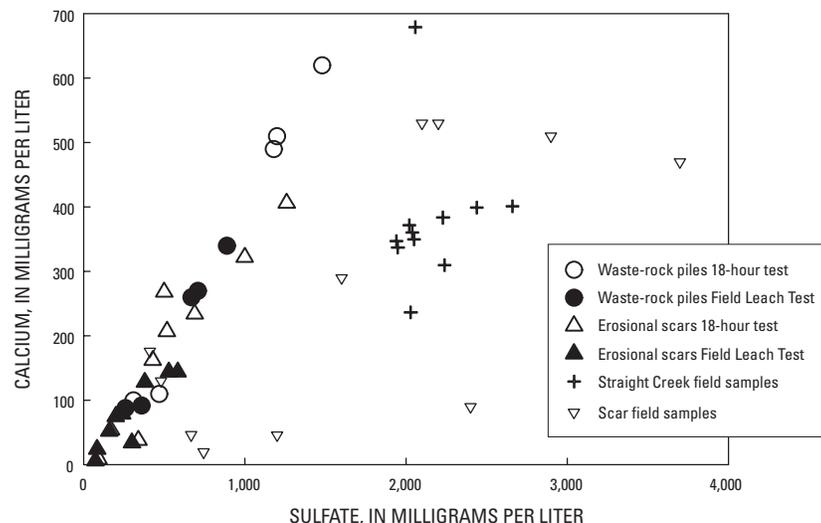


Figure 36. Calcium (Ca) plotted against sulfate (SO_4) concentrations for mine waste-rock leachates, erosional-scar leachates, and erosional-scar surface-water samples collected in the field from areas near Questa, New Mexico (field data are from Verplanck and others, 2006).

amorphous material are the most abundant minerals both on the surface of the waste-rock piles and on the erosional scars. Considerable supergene weathering of both the waste-rock and scar materials is indicated by the presence of sulfate and clay minerals (for example, jarosite, gypsum, kaolinite). Comparison of the geometric means of the bulk-chemistry constituents reveals that the mine waste-rock piles are ≥ 20 percent higher than the erosional scars for Ca, Na, Ti, S, Ba, Be, Cu, Mn, Mo, Ni, Sr, Th, Y, and Zn. The erosional scars have fairly wide concentration ranges for some elements, but their geometric mean is ≥ 20 percent higher than the mine waste-rock piles for iron, phosphorus, and lead.

The composited <2-mm size fractions from five mine waste-rock piles, nine erosional-scar areas, a less-altered site, and a slurry pipe grab sample were subjected to two back-to-back leaching procedures. The first procedure, the Field Leach Test (FLT), is a short-duration leach (5-minute shaking and 10-minute settling) and is intended to leach readily soluble materials. The FLT was immediately followed by an 18-hour end-over-end rotation leaching procedure, which is similar to the USEPA 1312 procedure. The end-over-end rotation results in considerable particle-size reduction over the course of the procedure. These leaching procedures can be used to evaluate potential metal release to receiving waters.

The waste-rock material generally is acid generating but appears to have pH buffering capability over time. The pH of the waste-rock leachates varies between 3.0 (Sugar Shack West) and 6.2 (Old Sulphur Gulch). With the exception of Sugar Shack West, the pH rises between the FLT and the 18-hour test. Some elements increase in concentration between the FLT and 18-hour procedures, and others decrease. Generally, the elements that increase over the 18-hour period include Ca, Cd, K, Mg, Mn, Mo, Rb, Si, Sr, and Ti. Generally, the elements that decrease over the 18-hour period include Al, B, Be, Cu, Dy, Er, Eu, Fe, Gd, Ho, Nd, Pb, Pr, Sm, Tb, Tm, Yb, and Zn. The decrease in iron and aluminum concentrations over

the 18-hour period are likely controlled by solubility reactions in response to the corresponding increase in pH. Precipitating phases of iron and aluminum can control trace-element concentrations by means of coprecipitation and sorption reactions, and we see evidence for this mechanism for several of the metals, including Be, Cd, Co, Cr, Cu, and Zn.

The pH of the erosional-scar leachates varies between 3.2 and 4.1, a much narrower range than for the mine waste-rock leachates. Unlike the mine waste-rock leachates, the erosional-scar leachates exhibit little difference in their pH values between the two leaching procedures. The elemental content of the erosional-scar leachates is highly variable between scars, which results in a large range of values for several elements. When the elemental concentrations in the waste-rock leachates are compared with concentrations in the erosional-scar leachates, generally the waste-rock leachate concentrations fall at or below the upper concentration range of the erosional-scar leachate compositions. One notable exception is molybdenum, which is higher in the waste-rock leachates. Because of the low pH of the scar leachates ($\text{pH} < 4.1$), many metals can be mobilized and remain in solution, the exception being anionic species, such as molybdenum, which are less mobile under acidic conditions.

Comparison of Straight Creek leachate compositions with the composition of Straight Creek erosional-scar drainage and storm-runoff waters shows that the FLT and 18-hour leachates have substantially lower element concentrations. However, the overall trends (that is, signatures or fingerprints) between elements are similar between the leaching tests and drainage samples. This finding illustrates that these (or any) leaching procedures cannot provide quantitative concentrations of actual waste-rock or scar contributions to surface or ground water. However, they can provide qualitative information about the likely chemical composition of porewater within the waste-rock piles and erosional scars.

The source material for the Capulin and Sugar Shack West waste-rock piles appears to be different from the other three waste-rock piles and similar to the source material for the erosional-scar areas. The leachate-pH values for the Capulin (pH 3.7 and 4.1) and Sugar Shack West (pH 3.2 and 3.0) waste-rock piles are in the same range as those of the erosional scars. In contrast, the leachate pH values for the Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South piles are higher and show some evidence for acid buffering with increased leaching contact time and agitation. Leachates from these three piles contain more calcium relative to sulfate, which indicates that calcite dissolution is taking place in addition to gypsum dissolution. Also, leachate sulfur isotopes for the Capulin and Sugar Shack West piles are similar to isotope values for sulfate in the scar areas and lighter than the leachate sulfur-isotope values from the Old Sulphur Gulch, Sugar Shack Middle, and Sugar Shack South piles. The Capulin and Sugar Shack West piles are older than the other three piles and reflect the shallow-earth materials removed at the beginning of open-pit mining, whereas the younger three piles consist of deeper, less-oxidized material with less pyrite and more carbonate.

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