Questa Baseline and Pre-mining Ground-Water Quality Investigation, 7. A Pictorial Record of Chemical Weathering, Erosional Processes, and Potential Debris-flow Hazards in Scar Areas Developed on Hydrothermally Altered Rocks

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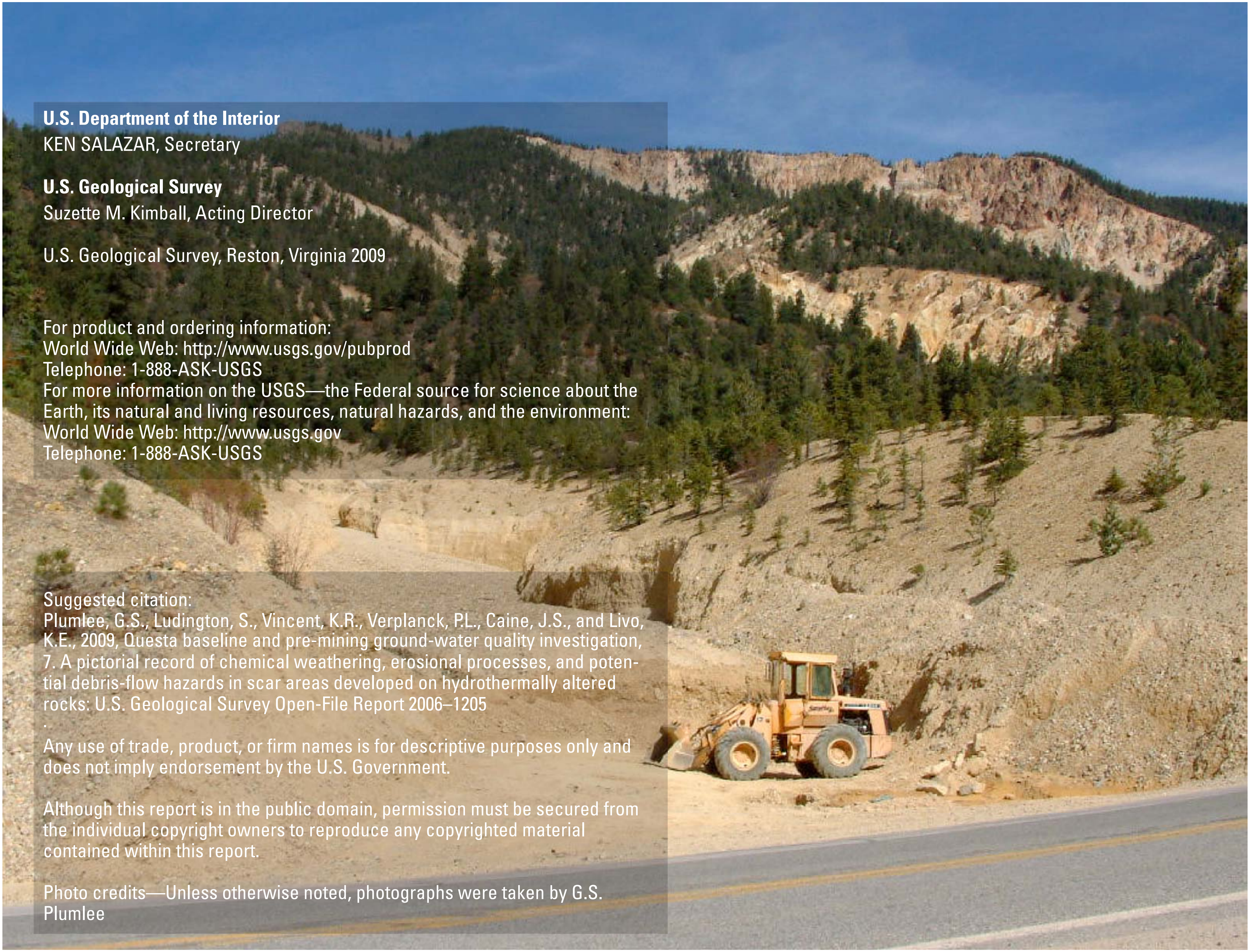
Hottentot scar, Red River Valley, NM–photo by G.S. Plumlee



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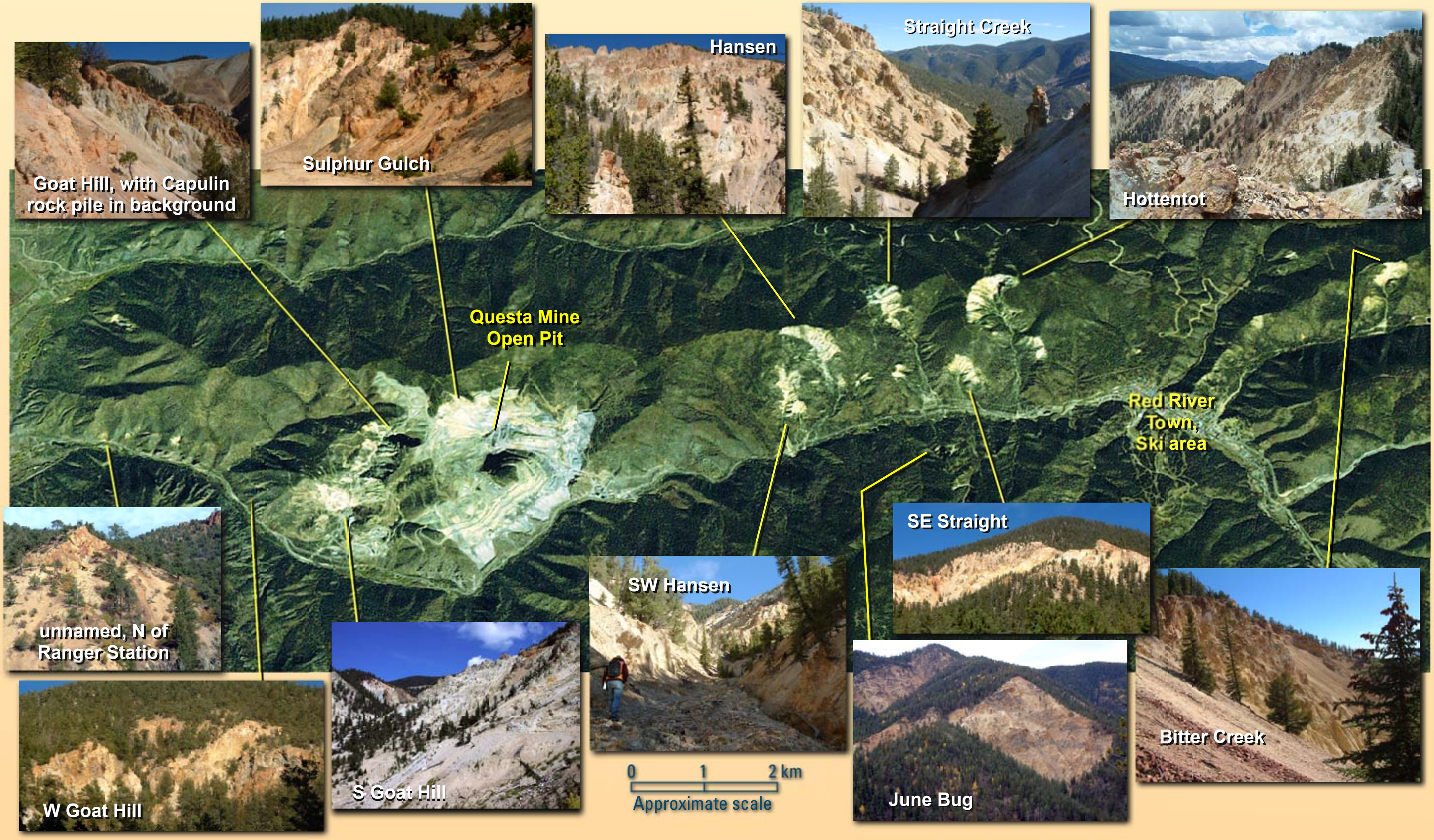
1 Introduction



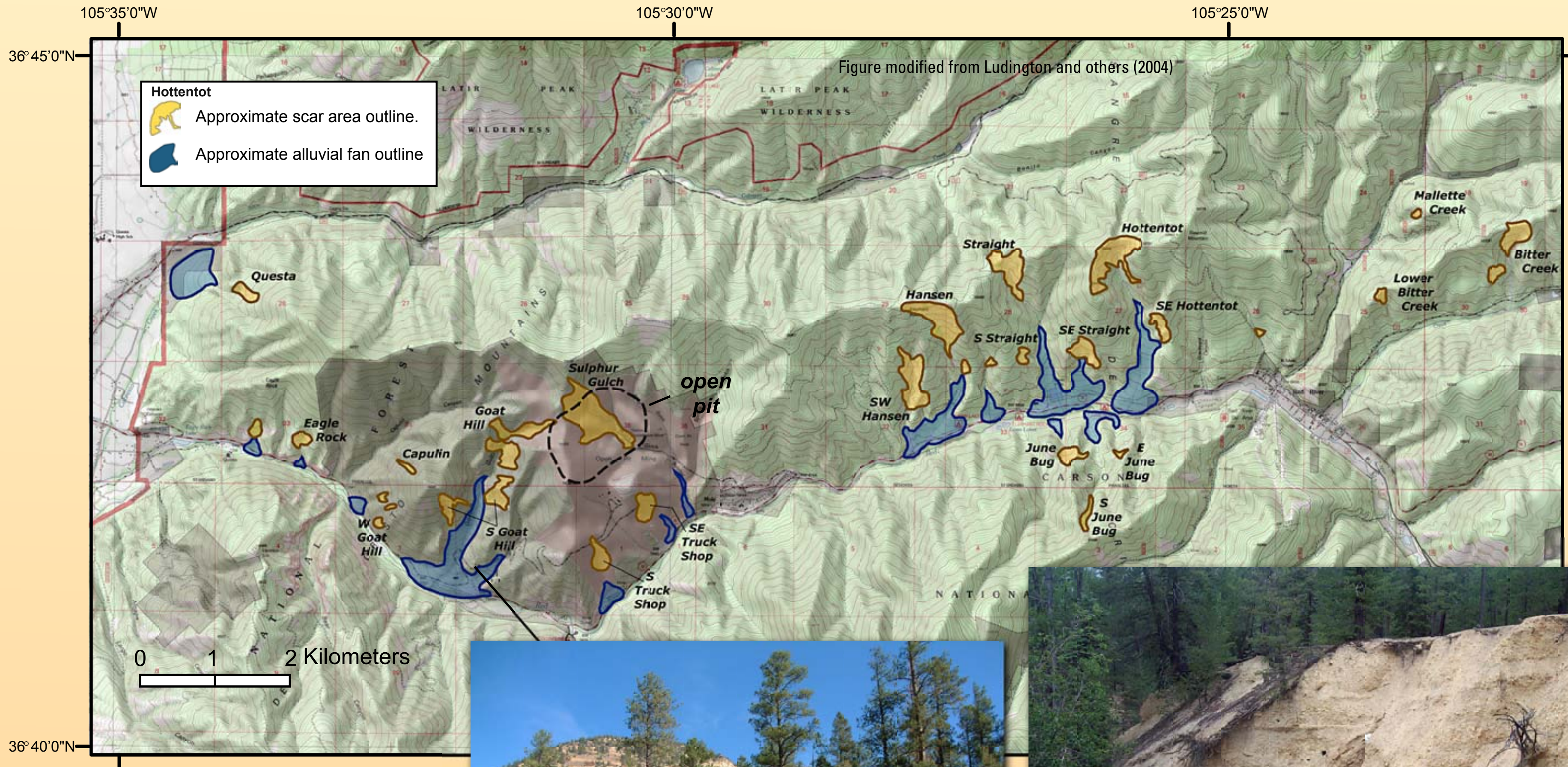
A number of natural erosional scars are readily visible in a satellite image of the lower Red River Valley (Above). Accompanying photographs of most of the major scars highlight their rugged topography and scenic beauty. The figure is modified from Ludington and others (2004). The satellite image is from IntraSearch.

Both historical underground mining and larger-scale modern open-pit and underground mining at the Questa Mine (noted on the left central portion of the satellite image) have extracted molybdenum from mineralized rocks beneath the Sulphur Gulch and Goat Hill scars.

Erosional scar areas developed along the lower Red River basin, New Mexico, reveal a complex natural history of mineralizing processes, rapid chemical weathering, and intense physical erosion during periodic outbursts of destructive, storm-induced runoff events.

The scar areas are prominent erosional features with craggy headwalls and steep, denuded slopes. The largest scar areas, including, from east to west, Hottentot Creek, Straight Creek, Hansen Creek, Lower Hansen Creek, Sulfur Gulch, and Goat Hill Gulch, head along high east-west trending ridges that form the northern and southern boundaries of the lower Red River basin. Smaller, topographically lower scar areas are developed on ridge noses in the inner Red River valley.

Several of the natural scar areas have been modified substantially as a result of large-scale open-pit and underground mining at the Questa Mine; for example, much of the Sulfur Gulch scar was removed by open pit mining, and several scars are now partially or completely covered by mine waste dumps.



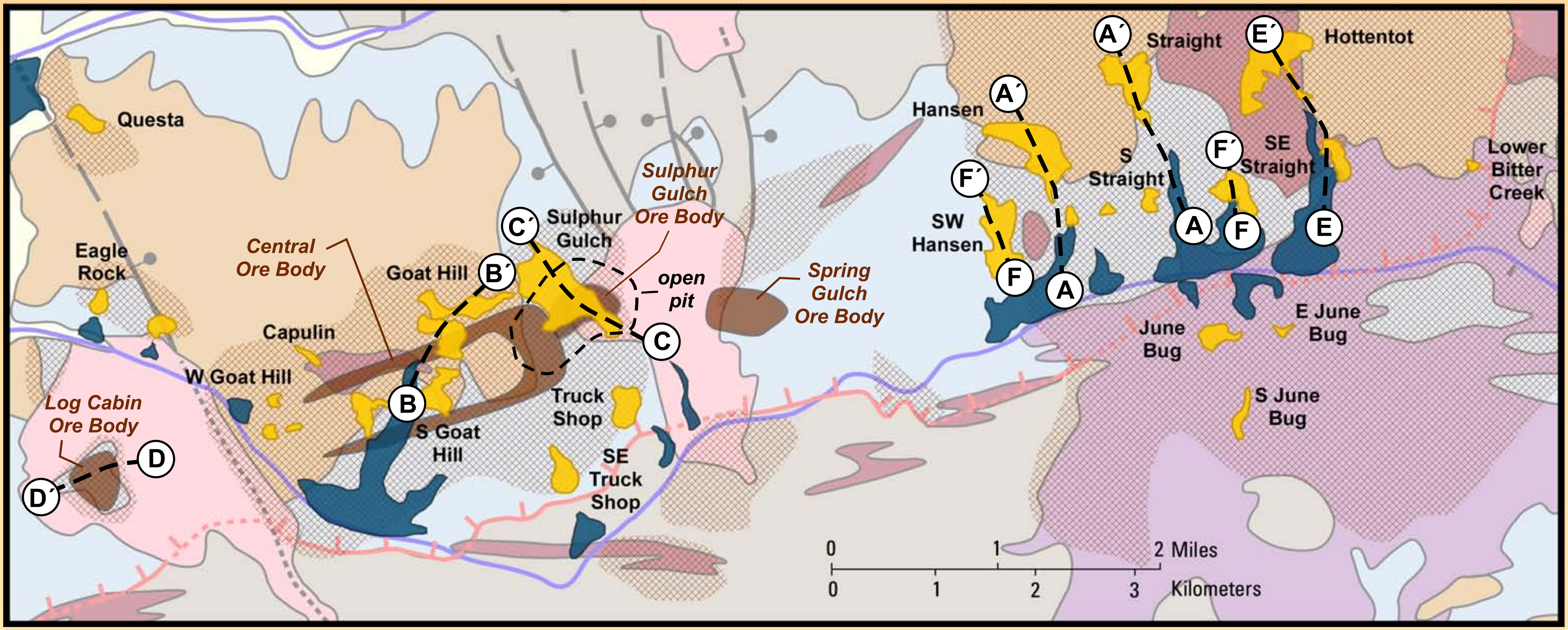
(Upper photo) View looking north of a road cut in the toe of the Goat Hill alluvial fan. The grade of NM Highway 38 (lower foreground) illustrates the steep topographic gradient on the downstream side of the fan.

(Upper right photo) The Red River has cut through the toe of the Hansen alluvial fan.

Each scar area has an associated alluvial fan deposit, which is constructed of material eroded from the scar and which extends from near the scar base to the Red River. Most of the debris fans have pushed the river channel toward the opposite side of the valley. Also, most of the fans have impeded the flow of the Red River, resulting in a shallow river gradient upstream from the fan and steep gradient immediately downstream. This is particularly noticeable on the drive from Questa to Red River, where NM Highway 38 undergoes a series of climbs over the Hansen, Straight, and Hottentot debris fans.

This photographic essay describes weathering and erosion processes in the scar areas and their associated alluvial fans. The photographs provide important insights into natural environmental conditions that existed in the lower Red River basin between the towns of Questa and Red River prior to mining. The photographs also illustrate the landslide and debris-flow hazards posed by the scars, especially during large summer thundershowers.

3 *Hydrothermally altered and mineralized rocks underlie the scar areas*



This geologic map (above) shows the distribution of major rock types, hydrothermal alteration, underground molybdenum ore bodies, and scar areas and their associated alluvial fans along the lower Red River valley. *The geologic map is modified from Lipman and Reed (1989).*

F´ – F **Line of section along a scar**
See next page for explanation and a schematic section showing distribution of rock and alteration types beneath each scar.

Hansen — **Erosional scar**

Alluvial fan

Spring Gulch Ore Body — **Known molybdenum ore body**
Mostly underground, except for small portions of the Sulphur Gulch and Log Cabin ore bodies that were exposed at the ground surface by erosion.

Areas of hydrothermal alteration mapped on the ground surface
Also includes some pre-intrusive regional alteration.

Fault
The cross bar and ball are located on the down-dropped side of the fault.

Granite intrusive rocks
Intrusion and crystallization of the magmas that formed these rocks also produced the hydrothermal fluids responsible for molybdenum mineralization and some of the alteration.

Rhyolite intrusive rocks

Questa Caldera margin
The cross bars point toward the interior of the caldera.

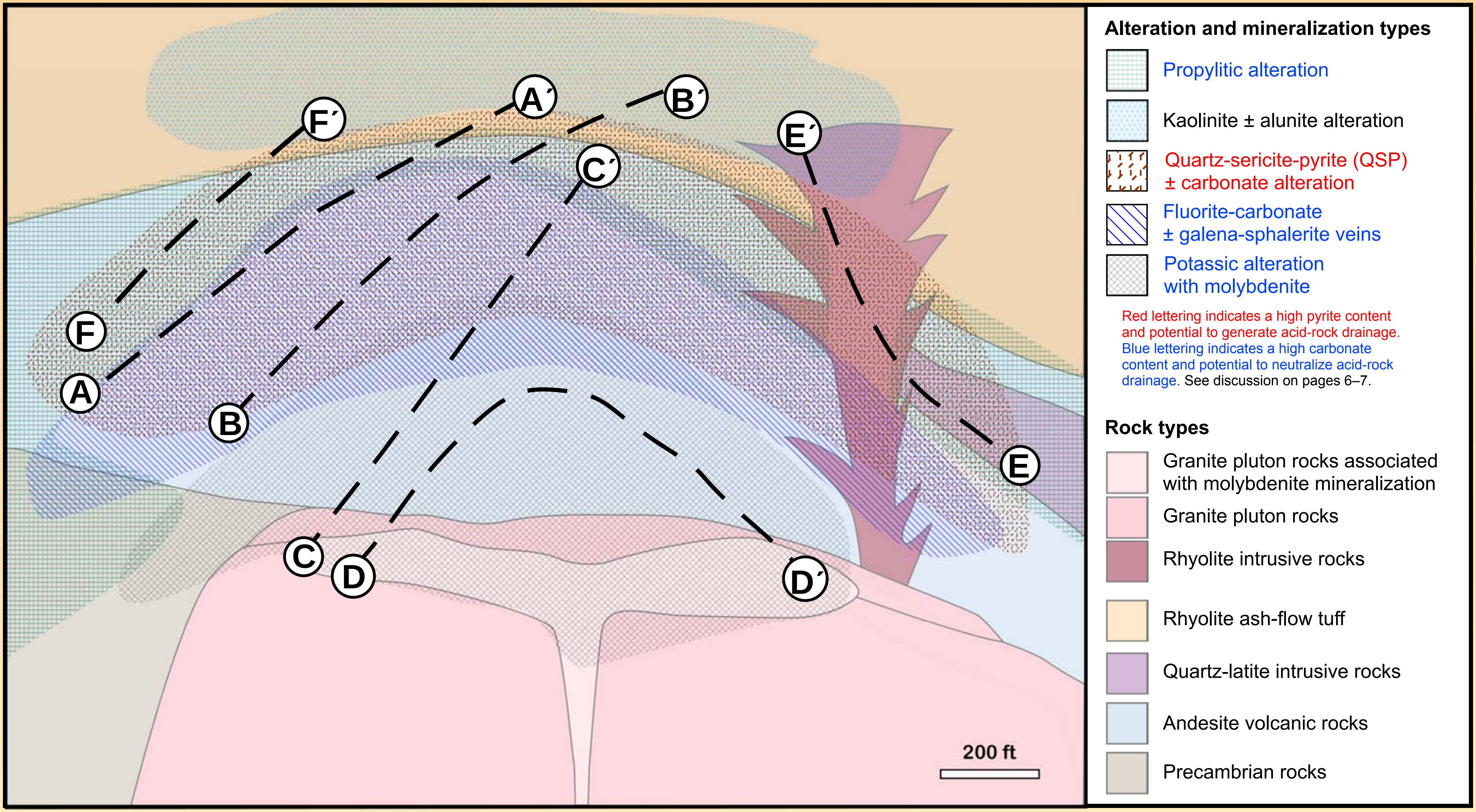
Rhyolite volcanic ash-flow tuff
Eruption of this tuff created the Questa Caldera.

Quartz-latite intrusive rocks

Andesite volcanic rocks

Precambrian rocks

The scar areas and alluvial fans are developed on bedrock that has been highly mineralized and altered. Molybdenum mineralization and related alteration were produced by magmatic-hydrothermal fluids released during the crystallization of a series of granitic magmas that intruded older volcanic, intrusive, and Precambrian rocks in several places along the southern margin of the Questa Caldera. Two molybdenum ore bodies were partially exposed by erosion at the ground surface prior to mining, including the ore body in Sulphur Gulch that became the focus of open-pit mining at the Questa Mine, and the Log Cabin ore body to the west of the Questa Mine. Two other ore bodies in the subsurface have been identified by drilling; of these, the Central Ore Body is currently the focus of large-scale underground mining at the Questa Mine. Although granite intrusive rocks similar to those associated with the Central, Sulphur Gulch, Spring Gulch, and Log Cabin ore bodies have not been identified beneath the eastern scars (Hansen, Straight, Hottentot), they are likely present in the subsurface.

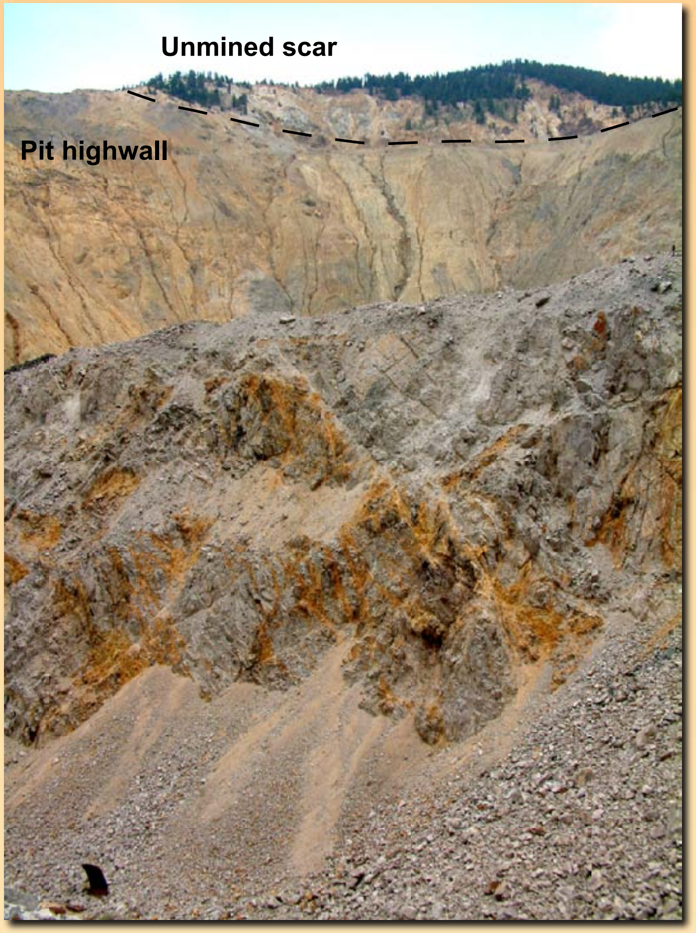


Different types of hydrothermal mineralization and alteration occur in specific zones around each of the granite intrusions, as shown in the schematic cross-sectional view above. Erosion of mineralized rocks around each of the granite intrusions has exposed a variety of mineralization and alteration types in each of the scar areas. The scars are most prominently developed on andesite volcanic rocks and quartz-latite intrusive rocks that have been highly altered to a quartz-sericite-pyrite (QSP) alteration assemblage. Molybdenum ores were first discovered outcropping in lower Sulphur Gulch, where erosion in the lower portion of the Sulphur Gulch Scar had cut through the QSP-altered volcanics into the underlying granite intrusion and high-grade molybdenite mineralization (see C–C′ on the cross section above). Erosion has almost completely removed the QSP-altered volcanics from above the Log Cabin ore body (D–D′ above).

This schematic cross section (above) shows the distribution of hydrothermal alteration and mineralization zones around a generalized granite intrusion of the lower Red River Valley. The labeled heavy black lines depict the schematic level of erosion relative to the alteration and mineralization zones exposed in scar areas identified on the maps on pages 2 and 3: A–A′ — Straight Creek, Hansen Creek; B–B′ — Goat Hill; C–C′ — Sulphur Gulch; D–D′ — Log Cabin ore body; E–E′ — Hottentot Creek; F–F′ — various inner valley scars such as SW Hansen, SE Straight, etc. *The cross section is modified from those presented in Martineau and others (1977) and Ludington and others (2003).*

5

This photo of the Questa open pit and uphill remnants of the Sulphur Gulch scar reveals a cross section of mineral zoning across one of the mined ore bodies. Quartz-sericite-pyrite (QSP)-altered andesites are exposed in the unmined scar and the upper portions of the pit highwall. At intermediate levels is a transitional zone of QSP alteration with some carbonate-fluorite veins. The foreground shows pink, molybdenite-mineralized, potassically altered, granite intrusive rocks crosscut by carbonate-fluorite veins; iron in these carbonates is being oxidized to orange iron hydroxides.



Carbonate-containing propylitic alteration occurs on the upper and lateral fringes of the mineralized systems along the Red River. In the photo to the left, green, propylitically altered andesites in the uppermost Questa open pit are cross-cut by a fracture zone along which the andesites have been altered to QSP; oxidation of pyrite to iron hydroxides causes the orange color. QSP alteration of andesite volcanic rocks is characteristic of the uppermost portions of most scar areas.

QSP alteration is typically associated with intense stockwork fracturing of the rocks. This photograph shows stockwork fractures in QSP-altered andesites that are exposed in a gully bottom along the Straight Creek scar. The orange color highlighting the fractures results from precipitation of iron hydroxide minerals by acid stream waters.

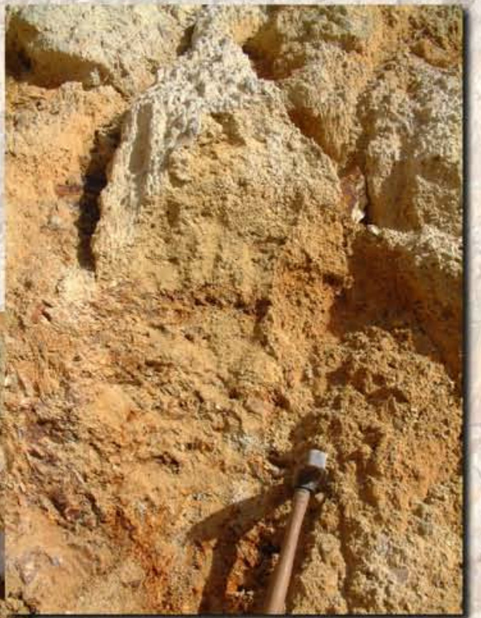
Dark gray molybdenite veins crosscut light pinkish-gray, granite intrusive rock in the underground ore body at the Questa mine.

Stockwork fractures filled with pyrite (green-gold) and quartz (gray) cross-cut QSP-altered andesite in this photo of a sawed rock sample collected from Straight Creek. The white blebs are crystals of feldspar that have been hydrothermally altered to sericite (a fine-grained white mica).

The scar areas form by acid-weathering and erosion of pyrite-rich rocks

All of the scar areas are developed on pyrite-rich, hydrothermally altered andmineralized volcanic rocks. When pyrite and other iron sulfides react with atmospheric oxygen and water, they produce acidic waters that are enriched in sulfuric acid and dissolved metals such as iron; these types of waters are termed "acid-rock drainage". These acid waters then react with other minerals in the rock, and can leach substantial quantities of other elements such as sodium, calcium, silica, and aluminum, and heavy metals such as zinc, from the rocks into the waters. Some of the dissolved iron reprecipitates as jarosite and iron hydroxides. The acid waters also may partially convert aluminosilicate minerals in the rocks to clays. Evaporation of the acid waters during dry periods leaves behind a mineralogically complex array of evaporative sulfate salts such as gypsum (a calcium sulfate) and copiapite (an iron sulfate).

Natural acid-rock drainage is present in most scars. The waters have pH around 2.5 to 3. Very high levels of dissolved iron cause the orange-brown color.



4) The most intensely weathered rock contains only small fragments of the original QSP-altered andesite, cemented within a matrix of clays, secondary iron minerals, and evaporative sulfate salts.

Increasing intensity of weathering and oxidation

3) More intense oxidation and weathering breaks the rock apart along the fractures, and begins to alter the rock fragments to clays, secondary iron minerals, and soluble salts.

2) Initial oxidation and weathering of the rock occurs along the stockwork fractures and results in the precipitation of gypsum and orange iron hydroxides and hydroxysulfates in the fractures.

1) Unoxidized andesite that occurs in the stream bottoms is altered to quartz-sericite-pyrite (QSP), and is crosscut by gray stockwork fractures that are filled with quartz and pyrite. Pyrite grains are visible as bright brassy specks throughout the rock.

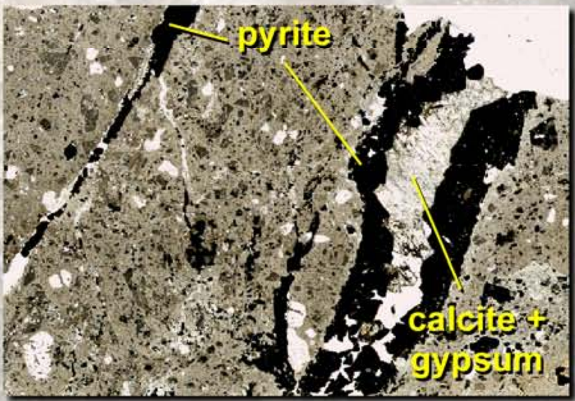
This photo shows a 20-cm diameter, platy mass of secondary gypsum crystals formed in a near-surface rock fracture due to the evaporation of acid waters. Shiny, well-formed gypsum crystals also are common throughout much of the highly weathered scar material.

7 *Acid waters are neutralized in the subsurface by small amounts of carbonate minerals in the rock*

Carbonate minerals such as calcite (a calcium carbonate), are generally present in small amounts in the QSP-altered rocks, particularly as fillings in the center of stockwork fractures. Manganese-rich carbonates are present in greater amounts in high-grade molybdenite vein ores. Small amounts of carbonates are also present in propylitically altered rocks on the upper portions and fringes of the mineralized systems.

Where present in the rock, carbonate minerals can react with and help neutralize the acid generated by sulfide oxidation. In the oxygen-rich near-surface weathering environment of the scars, the amounts of carbonate in the QSP-altered rock are insufficient to neutralize the acid generated by pyrite oxidation, and so highly acid waters and acid-sulfate weathering result. However, in the ground-water system out of contact with atmospheric oxygen, the carbonates are sufficient to neutralize all the acid in acidic waters that infiltrate from the surface, and so bedrock ground waters generally have near-neutral pH; however, the waters also have high levels of sulfate and some metals such as iron and zinc.

The high acid-neutralizing potential of carbonates in the high-grade molybdenite ores is demonstrated by the neutralization of acid surface waters seeping from the Questa Mine glory hole into to the underground workings.



This transmitted light photomicrograph of a thin section of QSP-altered andesite shows black (opaque) pyrite in a vein, with later calcite filling the vein center. The calcite has been partially replaced by secondary gypsum as a result of weathering. The field of view of the photograph is approximately 5 cm long.

Cut hand sample of a fluorite-carbonate vein from near the bottom Questa open pit.

Highly acidic surface-water runoff from the Goat Hill scar and various mine waste piles collects in the collapsed glory hole above the present-day underground block-cave mining operations of the Questa mine (left photo). These waters slowly percolate downward through the collapsed rocks, where they eventually encounter carbonate-rich mineralization.

By the time the waters reach the underground tunnels beneath the block-cave workings, they have near-neutral pH and lower concentrations of some metals. The waters also precipitate coatings and stalactites of calcite and iron minerals in the underground workings (photo below).

Rapid chemical weathering and physical erosion in the scars — a surface veneer

The scar areas are notable for their extremely high rates of chemical weathering and physical erosion. Rapid chemical weathering occurs due to the acid generated by sulfide oxidation.

The weathering of the bedrock greatly weakens the rock physically. Although evaporative sulfate salts help cement and strengthen the weathered material during dry periods, gradual dissolution of the salts during prolonged wet periods, such as during spring snowmelt or multiday summer monsoonal storms, destabilizes the weathered material. The scars also have acidic, poorly developed soils that do not support robust vegetation growth, which further enhances physical erosion. As a result, the scar areas are characterized by steep, denuded slopes.

In spite of the rapid physical erosion and chemical weathering, unoxidized bedrock is present in gully bottoms throughout most of each scar area, extending to within 30 meters or so of the high ridge crests. This indicates that chemical weathering and physical erosion are prevalent only in a relatively thin (6–30 m) veneer on top of unoxidized bedrock.

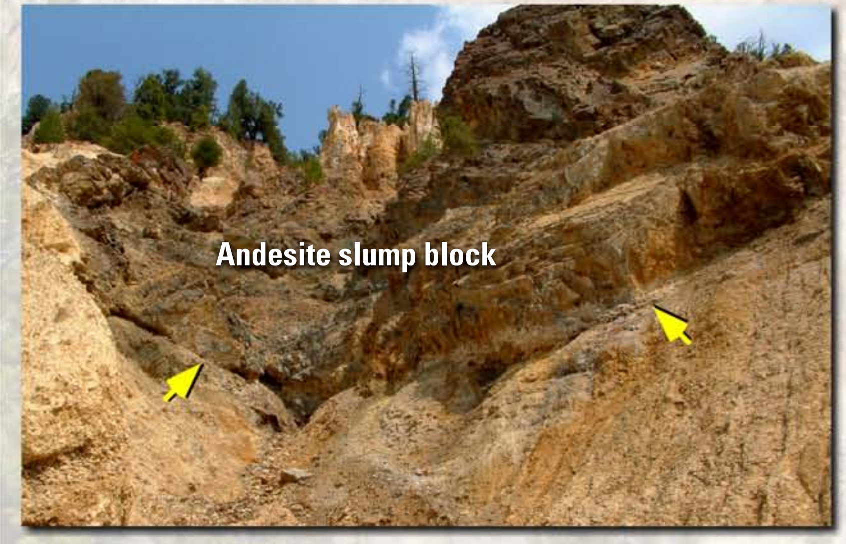
See Ludington and others (2004) and Plumlee and others (2005) for further details on the weathering processes in the scars.

A weathering profile in the Straight Creek scar (left photo) illustrates that the gray, unoxidized, QSP-altered rock in the stream bottom grades upward into weathered material with abundant jarosite and evaporative sulfate salts. Samples from increasing elevation in the profile (right photos above) illustrate that the rock is also progressively breaking apart into smaller and smaller fragments along the stockwork fractures.

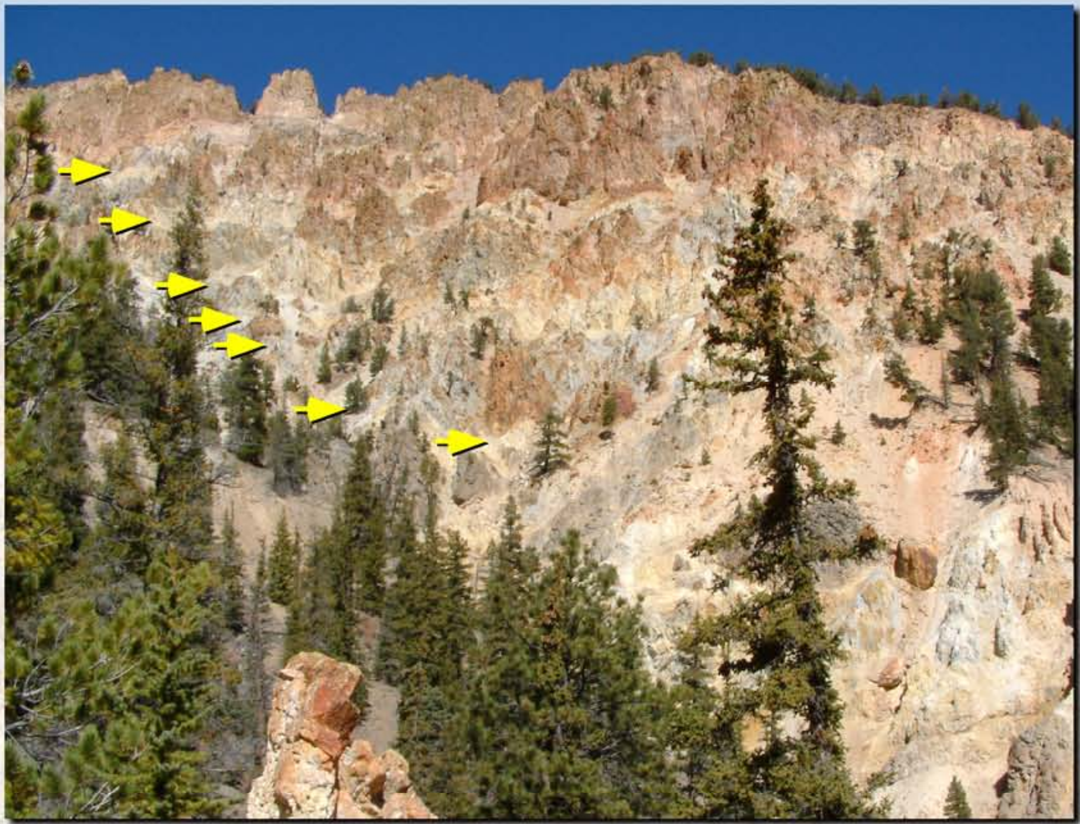
A block of pyrite-rich andesite (highlighted by the yellow arrows) that washed onto the uppermost Questa open pit bench from the upper Sulphur Gulch scar has substantially decomposed after less than twenty years. The white arrow points to decomposed material from the boulder.

Unoxidized QSP-altered bedrock (lower portions of photo to the right) occurs in gully bottoms to within 30 meters of the top of the Straight Creek scar, indicating that the weathered scar material is a relatively thin surface veneer.

The scar areas grow upslope and outward at their headwalls by oversteepening, slumping, and landsliding of the weakened weathered material. Rocks that escaped intense pyritic alteration, such as some blocks of andesite and most rhyolite tuff, do not weather rapidly, but instead creep downhill as coherent slump blocks on top of the weathered material.



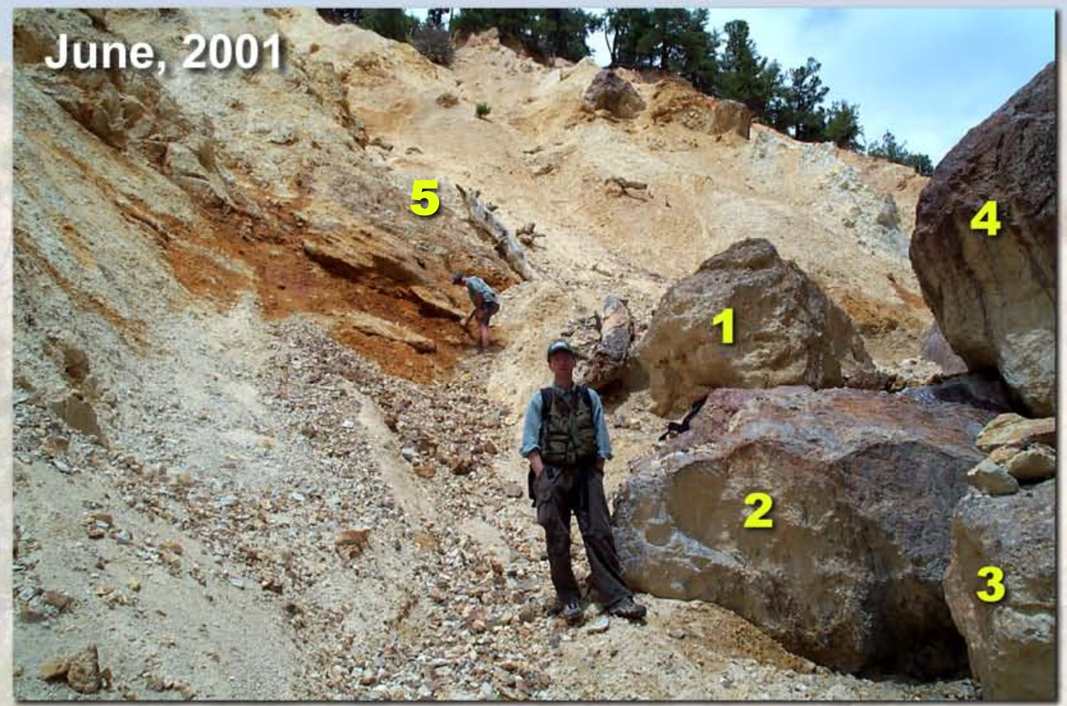
In the upper Sulphur Gulch scar, a large (> 10-m wide) brown slump block of propylitically altered andesite escaped intense QSP alteration and therefore is not extensively weathered. The block is creeping downhill along a shear contact (yellow arrows) over highly weathered, clay-rich material.



The Hansen scar is marked by a series of slump blocks of slightly to moderately altered rhyolite ash-flow tuff (pink, tan, and gray-colored) moving downslope over highly weathered, QSP-altered andesite volcanic rocks (yellowish-tan color). Each yellow arrow on the photo above marks the base of a slump block.

Closeup of a small fir tree growing on the steep slopes of a scar area. Due to continuing downhill creep of the weathered material, the tree has had to compensate in its growth to maintain a vertical growth direction. Photo by Rich Wanty.

Closeup of the upper Hansen scar showing jumbled blocks of slightly to moderately altered rhyolite ash-flow tuff that are slowly moving downslope on top of more highly altered and weathered rocks. Photo by Jonathan Caine.

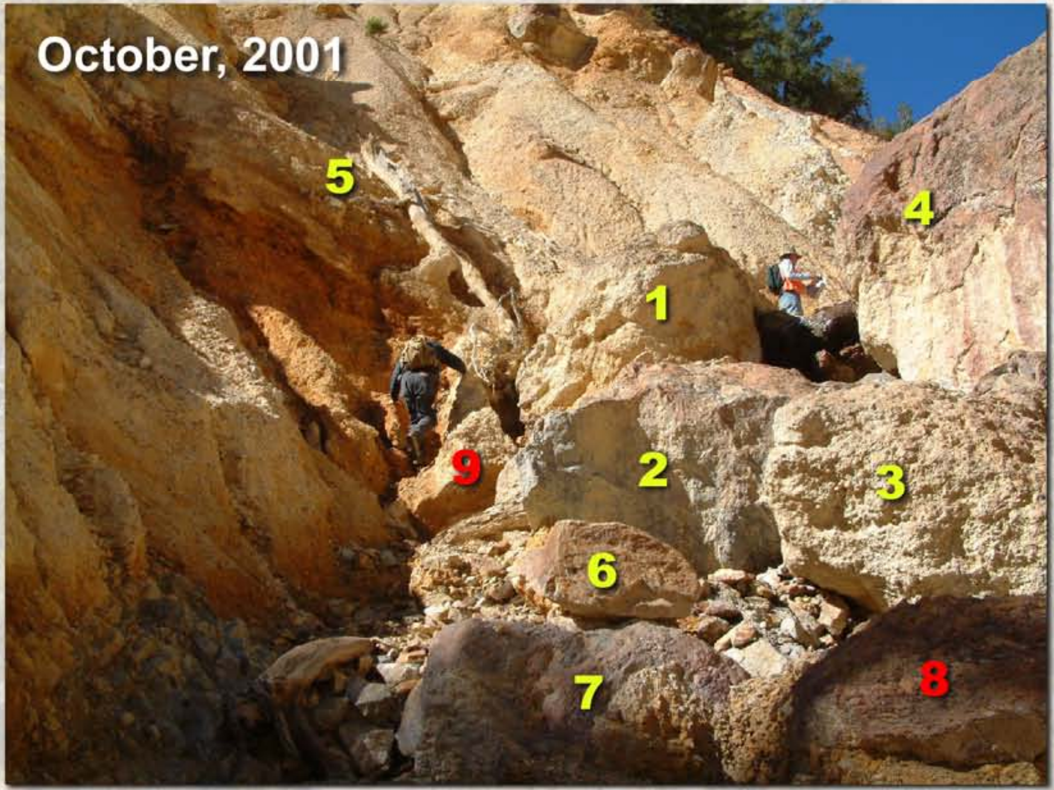


A series of photos taken at a site within the Straight Creek scar area illustrates the extreme amounts of erosion that can occur as a result of runoff during summer cloudbursts.

The yellow numbers mark rocks and a tree stump in the main channel that either remained within the field of view or were exposed by erosion over the 1.5-year time span of the photos. The red numbers mark rocks that were exposed by runoff-induced erosion between July, 2001, and October, 2001, and were then removed by runoff in one or more thunderstorms between October, 2001, and October, 2002. Altogether, it appears as though up to 1.5 meters of material, including several large boulders, was eroded from the channel at this spot during runoff from several storms. Note the gray-green unoxidized bedrock exposed in the channel bottom in 2002.

The photo sequence indicates that runoff from short but intense summer thundershowers effectively removes the loose material from the channel bottoms, but does not erode appreciable amounts of material from the scar slopes. The evaporative sulfate salts cementing the weathered veneer likely do not dissolve rapidly, and so inhibit water infiltration and rapid erosion. The denuded slopes act as funnels for runoff into the main channel.

In contrast, the greatest erosion of weathered material from the scar slopes and accumulation of this material in the channel bottoms likely occurs during prolonged periods of moisture (such as snowmelt or steady monsoonal rains) when the cement of soluble sulfate salts has the greatest time to dissolve, thereby weakening the weathered veneer.



11 Ferricrete deposits form where acid waters percolate through accumulated sediments

At places where sediments can accumulate for sufficiently long periods of time in the stream bottoms, the acidic, iron-rich stream waters percolate down through the sedimentary material and cement it with orange to brown iron hydroxide minerals to form ferricrete deposits. The ferricrete deposits typically form just above the contact between the sediments and the underlying bedrock. They are also quite resistant to erosion, and serve as aquitards that inhibit ground-water flow into the sediments from the bedrock and vice versa.

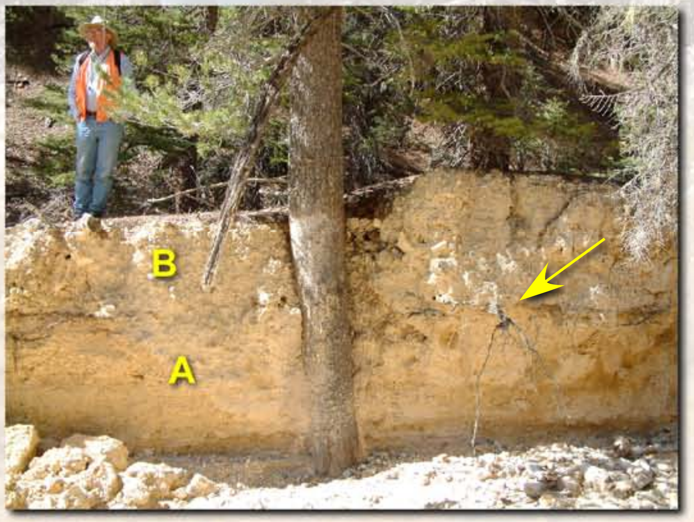
Sedimentary material that collected behind a dam of large rocks and a log in the lower Straight Creek scar channel persisted for long enough that it became cemented by iron oxides to form a ferricrete deposit. Gray-green QSP-altered but unweathered bedrock is present directly beneath the brown ferricrete. After this photo was taken in October, 2001, storm runoff has removed the log and smaller rocks from the dam, and is now eroding the ferricrete.

Ferricrete that formed in the main stream channel of the Lower Hansen Creek scar is now slowly being eroded. Note the brown color of the acidic, iron-rich stream water.

Ferricrete deposits also formed in the past, most typically at the breaks in slope between the paleo stream channels and adjacent ridges. Cliff-forming erosional remnants of these ferricrete deposits are present in each of the scar areas, such as Lower Hansen (left photo) and lower Straight Creek (above photo). Large ferricrete blocks that have broken off from these deposits are common in the scar channels and debris fans.

The alluvial fans are dynamic environments of material erosion, transport, and deposition

Extensive alluvial fans are present downstream from each of the scar areas. The fans receive copious quantities of material eroded from the scars, primarily during summer storm runoff events. The scar areas and debris fans are highly dynamic, with spatially and temporally variable erosion, transport, and deposition by periodic debris flows containing material ranging in size from boulders to silts and clays. The extent of erosion, transport, and deposition in the alluvial fans during a particular storm runoff event is a function of the amount of loose material available for transport in the scar areas and upper portions of the debris fans, coupled with the intensity of the runoff event.



Multiple periods of sediment deposition, followed by a major erosional event, are documented by this photo taken in the Straight Creek alluvial fan. The older tree in the center of the photo grew from a seed that fell on a ground surface that was then buried by material from debris flow A. A younger tree (just visible to the right of center) grew from a seed that fell on top of A, which was then buried by debris flow B; note the roots (indicated by the arrow) of the younger tree emanating from the break between the debris flow deposits. Material from both debris flows has subsequently been eroded to a depth of nearly 2 meters.

More than two-thirds of a meter of the upstream side of a tree growing outside the active Straight Creek channel has been abraded by over-bank flow during a debris flow event. Mud spatter from the debris flow reached an additional half meter up the tree trunk.

Material from a debris flow plugged a once-active channel in the Hottentot debris fan (above). Subsequent runoff was naturally diverted around the plug, and erosion has since cut a new, 1.5-m deep channel that flows to the east of the plug (indicated by arrows in the photo to the left).

Such complex variability in the distribution of channels and channel-filling material indicate that the subsurface geology and hydrology in the alluvial fans is also likely to be quite complex.

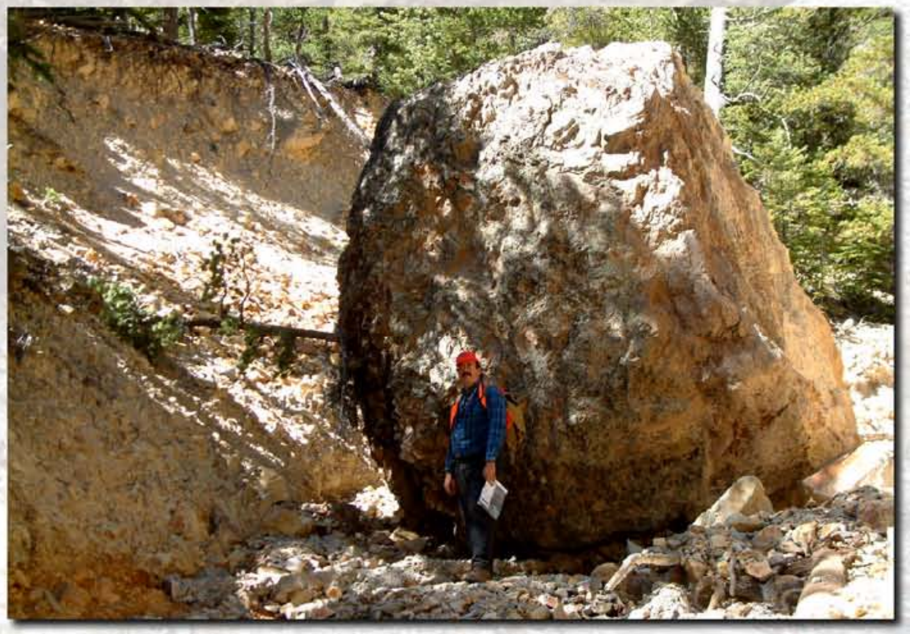
Hazards in the scar areas and alluvial fans during storm runoff events

There are many examples in both the scar channels and alluvial fans of the sheer power and destructive potential of storm runoff events. These demonstrate that both the scar areas and the debris fans, especially portions of the debris fans close to the active channels, are not safe places to be during intense thunderstorms and their subsequent runoff.

In nearly all of the scar areas, some stretches of the active channels are narrow with high walls. Such stretches should be avoided by hikers if rainfall is imminent, as it would be very difficult to escape from these stretches during a storm runoff event. (Right) Upper Hansen. (Below) Hottentot.

A ferricrete boulder estimated to weigh several hundred pounds was transported by overbank flow during storm runoff to its current position resting on a cut tree stump outside the active Straight Creek stream channel.

Runoff from a storm in early fall, 2002, caused extensive erosion of the banks of the main Hottentot Creek channel. This erosion led to the collapse of several large trees into the channel (left), and caused a 5-meter wide boulder to topple into the channel (right). Note the tree growing from what used to be the boulder top. Photos were taken around two weeks after the storm event.



It is well known that debris flows from the scar areas can reach the lower portions of the fans. As noted by Meyer and Leonardson (1990), there have been repeated instances recorded where debris flows crossed NM Highway 38, one of which (from the SW Hansen drainage) led to the fatality of a motorist in 1982. There are also numerous buildings, the Red River water treatment plant, and several campgrounds located on or near the fans that are potentially in the path of future debris flows.

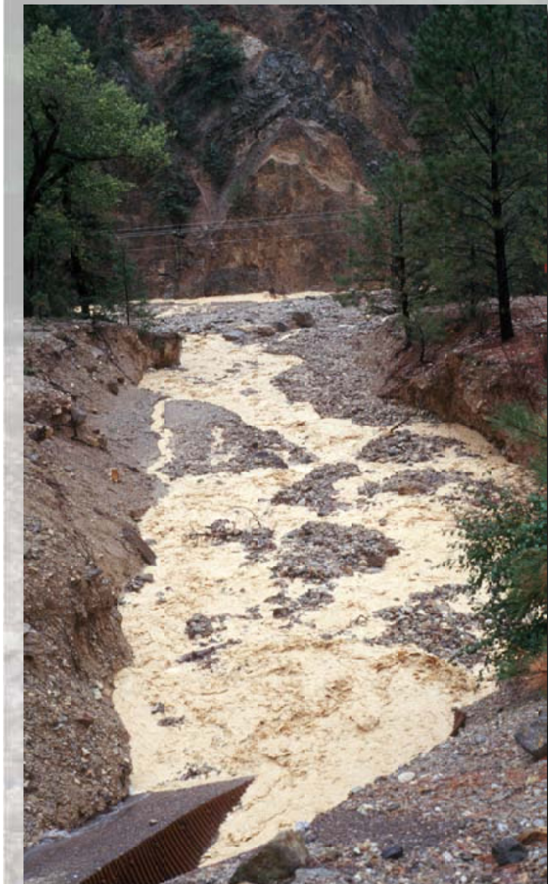
Further monitoring and assessment studies of debris-flow generation, transport, erosion, and deposition in the scar areas and alluvial fans are needed to develop a better understanding of how and when future debris flows might pose hazards to humans and built structures in the lower fans. For example, a network of telemetered rainfall gauges near each of the scar areas could provide an indication of major rainfall events that have potential to develop destructive debris flows. Further analyses of sediment erosion and deposition rates and patterns in both the scar areas and debris fans, tied to measured rainfall rates and snowmelt events, are also needed.

(Right) Two of three culverts under Highway 38 at Hottentot Creek were completely filled by material from the debris fan, as of this February 2002 photo.

(Left) The front-end loader for scale provides an indication of the amount of sediment that collected in the Lower Hansen channel at Highway 38 during storm runoff events in the summer of 2001.

15 *Effects of storm runoff from the scar areas on water quality in the Red River*

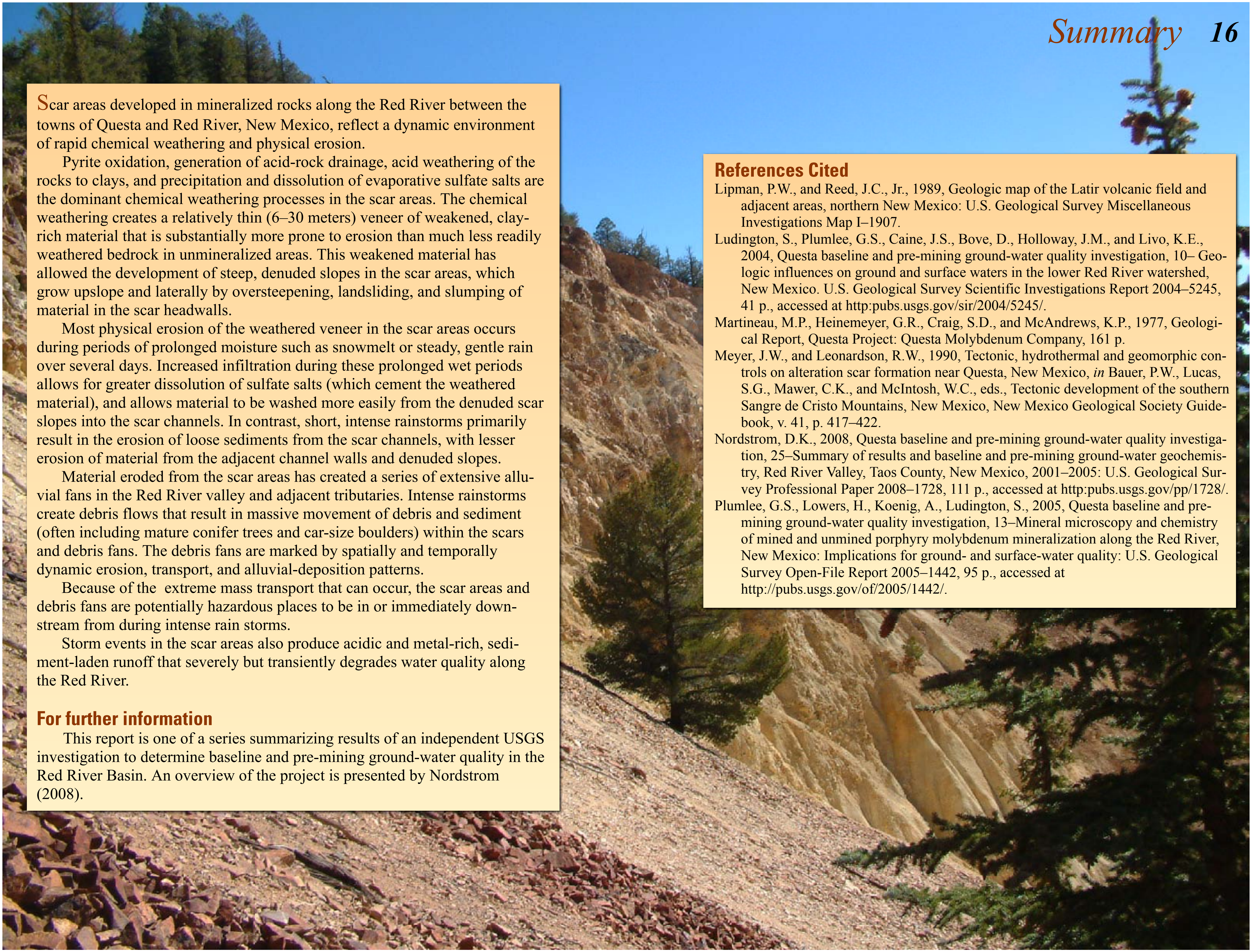
Runoff from storm events in the scar areas and debris fans is quite acidic and metal-rich, due to partial dissolution of soluble sulfate salts from the weathered material. In addition, the runoff waters carry very high levels of suspended sediments. Transient but substantial degradation of surface-water quality in the Red River occurs as a result of natural storm runoff from the scar areas and debris fans.



These photos show the effects of heavy storms in September, 2002, on water quality in the Red River and its tributaries that drain the scar areas.

Counterclockwise from left: Hansen Creek where it enters the Red River; SW Hansen Creek; the Red River below SW Hansen Creek, and; for comparison, the Red River below Hansen Creek during normal nonstorm conditions. As a result of the September storms, the pH at the Red River gauging station at the USDA Forest Service Questa Ranger Station dropped from near 7 to below 4. The suspended sediment load increased drastically in the Red River, as well.

All photos taken by Philip Verplanck.



Scar areas developed in mineralized rocks along the Red River between the towns of Questa and Red River, New Mexico, reflect a dynamic environment of rapid chemical weathering and physical erosion.

Pyrite oxidation, generation of acid-rock drainage, acid weathering of the rocks to clays, and precipitation and dissolution of evaporative sulfate salts are the dominant chemical weathering processes in the scar areas. The chemical weathering creates a relatively thin (6–30 meters) veneer of weakened, clay-rich material that is substantially more prone to erosion than much less readily weathered bedrock in unmineralized areas. This weakened material has allowed the development of steep, denuded slopes in the scar areas, which grow upslope and laterally by oversteepening, landsliding, and slumping of material in the scar headwalls.

Most physical erosion of the weathered veneer in the scar areas occurs during periods of prolonged moisture such as snowmelt or steady, gentle rain over several days. Increased infiltration during these prolonged wet periods allows for greater dissolution of sulfate salts (which cement the weathered material), and allows material to be washed more easily from the denuded scar slopes into the scar channels. In contrast, short, intense rainstorms primarily result in the erosion of loose sediments from the scar channels, with lesser erosion of material from the adjacent channel walls and denuded slopes.

Material eroded from the scar areas has created a series of extensive alluvial fans in the Red River valley and adjacent tributaries. Intense rainstorms create debris flows that result in massive movement of debris and sediment (often including mature conifer trees and car-size boulders) within the scars and debris fans. The debris fans are marked by spatially and temporally dynamic erosion, transport, and alluvial-deposition patterns.

Because of the extreme mass transport that can occur, the scar areas and debris fans are potentially hazardous places to be in or immediately downstream from during intense rain storms.

Storm events in the scar areas also produce acidic and metal-rich, sediment-laden runoff that severely but transiently degrades water quality along the Red River.

For further information

This report is one of a series summarizing results of an independent USGS investigation to determine baseline and pre-mining ground-water quality in the Red River Basin. An overview of the project is presented by Nordstrom (2008).

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