Figure 2. Alluvial ferricrete along Mineral Creek between Middle and South Forks of Mineral Creek (view to west). Outcrop is about 30 m thick and rests on granitoid porphyry bedrock. Ferricretes form in paleo-alluvial terrace deposits where terrace sands and gravels are cemented by iron oxyhydroxide minerals.

Figure 3. Alluvial ferricrete above mouth of Cement Creek (view to south). Kendall Mountain in distance.

Figure 4. Log in alluvial ferricrete along Middle Fork Mineral Creek is below and about 400 m downstream from Bonner mine. Note log cemented in place by iron oxyhydroxide cement. The radiocarbon age of this log is 790 yr B.P. Logs encased in ferricrete throughout the upper Animas River watershed range in age from modern to 9,150 yr B.P.

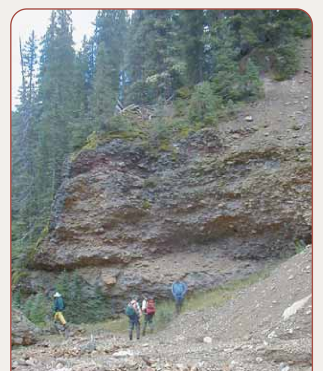
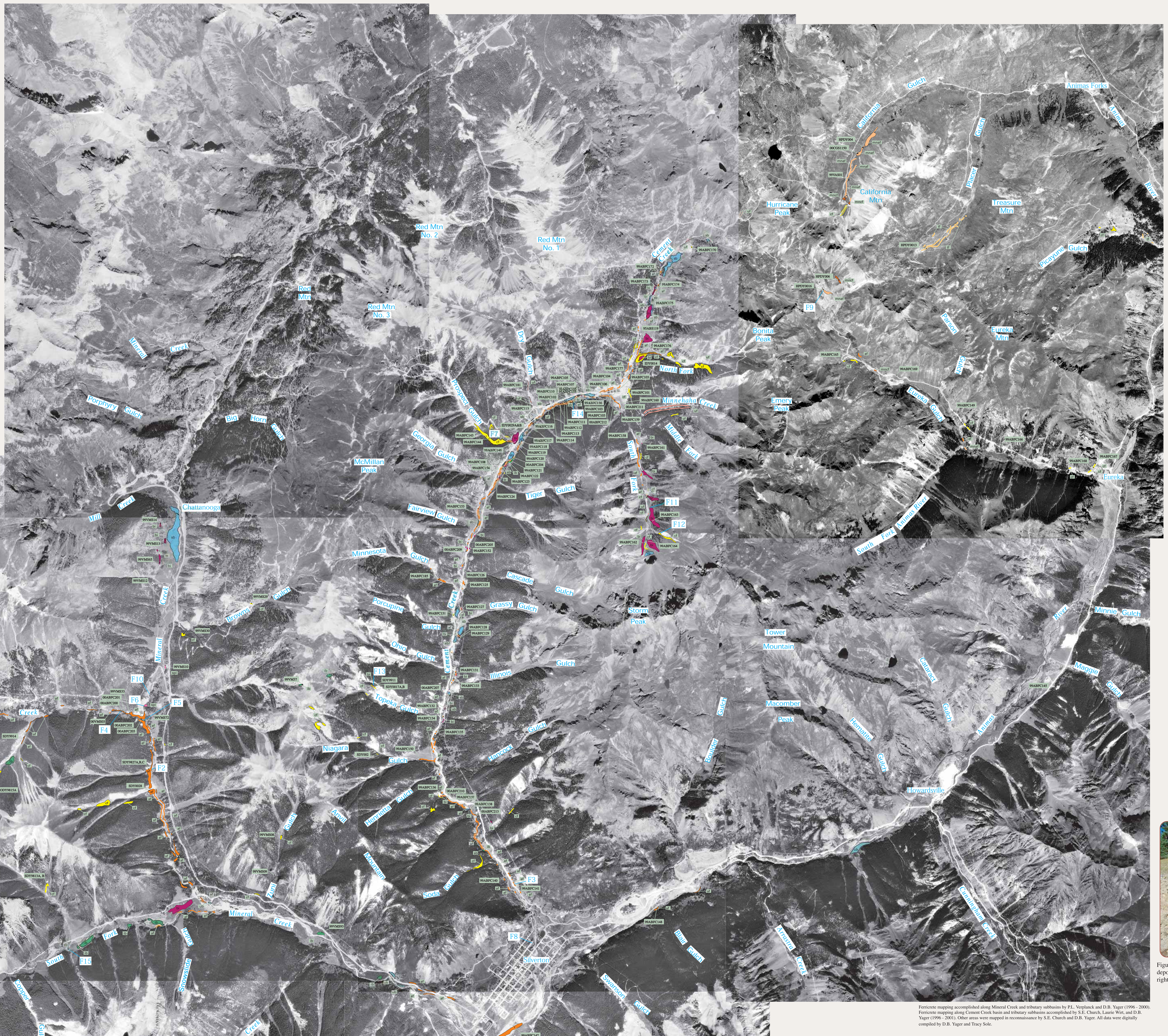


Figure 5. Alluvial ferricrete at mouth of Middle Fork Mineral Creek.



Base from U.S. Geological Survey 1997, 3.3 ft (1 m) resolution digital orthoquadrangles. Quadrangles used include Ironton, Handies Peak, Ophir, Silverton, and Howardsville.

Ferricrete mapping accomplished along Mineral Creek and tributary subbasins by P.L. Verplanck and D.B. Yager (1996–2000). Ferricrete mapping along Cement Creek basin and tributary subbasins accomplished by S.E. Church, Laurie Wirt, and D.B. Yager (1996–2001). Other areas were mapped in reconnaissance by S.E. Church and D.B. Yager. All data were digitally compiled by D.B. Yager and Tracy Sole.

SCALE 1:24 000

APPROXIMATE MEAN DECLINATION, 1998

Figure 6. An active iron spring located about 240 m above the confluence of Mineral Creek and Middle Fork Mineral Creek forms where organics and iron precipitates accumulate. Note acidophyllic, dark-green sphagnum moss at base of spring.

Figure 7. Iron spring in lower Prospect Gulch near head of Cement Creek (view to south). Bog iron and colluvial ferricrete deposits are preserved adjacent to spring.

Figure 8. Alluvial ferricrete at base of excavated foundation (town of Silverton). Builders commonly encounter ferricrete "hardpan" when excavating foundations throughout the town.

FERRICRETE, MANGANOCRETE, AND BOG IRON OCCURRENCES WITH SELECTED SEDGE BOGS AND ACTIVE IRON BOGS AND SPRINGS IN PART OF THE ANIMAS RIVER WATERSHED, SAN JUAN COUNTY, COLORADO

By
Douglas B. Yager, Stanley E. Church, Philip L. Verplanck, and Laurie Wirt

2007

CORRELATION OF MAP UNITS

sb	spi	ib	ub	af	cf	uf	mncf	mnaf	tf	bi

HOLOCENE
LATE PLEISTOCENE

DESCRIPTION OF MAP UNITS

sb — **Sedge bog (late Pleistocene to modern)**—Water-saturated ground that is colonized by acid-tolerant sedges, grasses, mosses, and willows with pH typically ranging from 3.2 to 5.5. Sedge bogs generally form at the base of hillslopes, at sites where the water table is intersected by the ground surface, and downslope from colluvial deposits on relatively flat lying valley fill, flood plains, and terraces. Substrate is spongy organic material that is transitional to buried peat and may include fine-grained silt. Sedge bogs may overlie or interfinger with iron bog and alluvial terrace deposits. Twigs and logs are present in the sedge bog and the peat deposits. Thickness in places may exceed 5 m

spi — **Iron spring (late Pleistocene to modern)**—Varicolored, brown to reddish-brown or orange deposits of impure hydrous iron oxides that form where water flows naturally from bedrock fractures or soil. Deposits consist of finely laminated deposits of goethite, amorphous iron oxyhydroxides, and locally schwertmannite, as well as acid-tolerant algae or mosses. Precipitates form where acidic springs discharge to the ground surface or a water body, often where bedrock fractures are intersected by surface topography. May occur on modern flood plain, on old terraces, or on hillslopes. Conifer needles are common; twigs and logs rare. Bedrock clasts are locally preserved. Damp surfaces often support growth of sphagnum moss. Thickness 0.1 m to more than 4 m

ib — **Iron bog (late Pleistocene to modern)**—Varicolored, predominantly brown to reddish-brown, but may be whitish-gray to yellow or orange, impure hydrous iron oxide deposits in water-saturated ground. Consist of oxides of iron, aluminum, and manganese compound precipitates. Precipitates form in acidic, poorly drained conditions by the oxidizing action of algae, iron (thiobacillus ferrooxidans)- and sulfur (thiobacillus thiooxidans)-oxidizing bacteria, or the atmosphere. Acidophyllic algae and mosses may be present. Substrate consists of hydrous iron oxyhydroxides (schwertmannite), amorphous iron oxyhydroxides, and goethite, which have porous textures ranging from thinly layered to irregular aggregates. Algal mats trap freshly formed oxyhydroxide-oxyhydroxysulfate precipitates. Clasts, logs, and twigs are locally preserved. Observed thicknesses range from 0.1 to 0.5 m

ub — **Undifferentiated bog (late Pleistocene to modern)**—Sedge bog or iron bog, as described above. Unit is undifferentiated because deposits were either identified from aerial photograph interpretation or were not accessible due to land ownership issues

af — **Alluvial ferricrete (late Pleistocene to modern)**—Brown to yellowish-brown, iron oxyhydroxysulfate-cemented sandstone or conglomerate; cement consists principally of goethite. Deposits are bedded to weakly stratified and consist mostly of heterogeneous subrounded to subangular pebbles and cobbles with occasional boulder-size clasts in an iron oxyhydroxide-cemented, clast-supported matrix, of coarse sand- to pebble-size sediment. Clasts are imbricated and dip upstream. Pebbles and cobbles in some places are coated with a fine filamentous iron oxyhydroxide cement similar in appearance to algae. Exceptional (as much as 30 m thick) alluvial ferricrete exposures preserved along the west side of Mineral Creek between South Fork and Middle Fork of Mineral Creeks, and near the mouth of Cement Creek near Silverton, consist of sandstone layers among coarse-grained graded beds of gravel, which are indicative of high-energy stream transport. Alluvial ferricrete deposits are either wet or dry at present. Along active flood-plain channels, such as Cement and Mineral Creeks, seeps and springs flow from premining ferricrete terraces. Sphagnum moss is frequently observed at seep zones, from 0 to 2 m from stream beds. Conifer logs are locally found within these deposits and the alluvium locally interfingers with peat. Alluvial ferricrete preserved several meters above the active channel is often dry and represents cemented alluvial fan remnants and stream terrace deposits. ^{14}C ages from logs and twigs recovered from these deposits range in age from modern to 4,960 yr B.P. Thickness, 0.5 to 30 m

cf — **Colluvial ferricrete (late Pleistocene to modern)**—Iron oxyhydroxysulfate-cemented deposits; varicolored, brown (predominant), reddish-brown to brownish-yellow with dark-brown stained clasts. Cement consists principally of goethite. Deposits are massive to weakly stratified subparallel to the current slope or drape existing topography; consist of mostly homogeneous angular, subangular, to subrounded pebbles, cobbles, and boulders in an iron oxyhydroxide-cemented, finer grained clastic to relatively clast free matrix. Cobbles are weakly imbricated and dip downslope. Clasts consist of subangular to subrounded pebbles in contact with silt- and sand-size sediment. Pebbles and cobbles are locally coated with a fine filamentous iron oxyhydroxide cement similar in appearance to algae. Few logs and twigs or other organic materials are preserved. Colluvial ferricrete deposits are either wet or dry, and are formed on hillslopes and in narrow debris channels where rock and soil could accumulate in colluvium, talus, and alluvial fan deposits. Source materials were derived from weathering of local bedrock that was transported less than a few kilometers. ^{14}C ages on wood fragments from colluvial ferricrete deposits have yielded radiocarbon ages ranging from 870 to 9,150 yr B.P. whereas ^{14}C ages of fully replaced casts of woody material and unidentified "organic carbon" have minimum ^{14}C ages ranging from 1,170 to 7,680 yr B.P. Outcrop thickness 2 to 7 m; maximum thickness unknown

uf — **Undifferentiated ferricrete (late Pleistocene to modern)**—Colluvial or alluvial ferricrete, as described above. Colluvial ferricrete likely is preserved on hillslopes several meters above tributary streams; alluvial ferricrete forms in alluvial terraces and fans

mncf — **Colluvial manganocrete (late Pleistocene to modern)**—Black to dark-gray, manganiferous-rich ferricrete. Scanning electron microscopy analyses indicate that matrix consists of Mn- and Fe-rich compounds. Unit description is similar to colluvial ferricrete (cf); however, manganocrete has manganese in sufficient concentrations, about 2.4 to 4.8 weight percent, to impart a black to dark-gray color. Some manganocrete outcrops are transitional toward more highly iron enriched ferricrete. The distribution of manganocrete is confined to areas that drain the manganese-rich veins along the Eureka graben, such as Placer Gulch, California Gulch, and the Eureka basin where the original, late 1800s Sunnyside mine adit was excavated. Thickness 0.5 to 3 m

mnaf — **Alluvial manganocrete (late Pleistocene to modern)**—Black to dark-gray, manganiferous-rich ferricrete. Scanning electron microscopy analyses indicate that matrix consists of Mn- and Fe-rich material. Unit description is similar to alluvial ferricrete (af); however, manganocrete has manganese in sufficient concentrations, about 2.4 to 4.8 weight percent, to impart a black to dark-gray color. Some manganocrete outcrops are transitional toward more highly iron enriched ferricrete. One deposit sampled in Eureka Gulch adjacent to the original Sunnyside mine adit near the former Lake Emma consists of finely layered, silt- to sand-size material at its base, which grades upward into a sequence of clay matrix supporting subangular to subrounded pebbles and cobbles and alternating interbedded coarse sands. This deposit is thought to represent an alluvial fan that was deposited into the former Lake Emma. A matrix, radiocarbon date of this deposit yielded an age of 8,000 yr B.P. The distribution of manganocrete is principally confined to areas that drain the Eureka graben, such as Placer Gulch, California Gulch, and the Eureka basin, where the original, late 1800s Sunnyside mine adit was excavated. Alluvial manganocrete deposits in the Animas River watershed, however, have been identified as far south as beyond Elk Park, south of Silverton. Thickness 0.5 to 4 m

tf — **Transitional colluvial manganocrete and ferricrete (late Pleistocene to modern)**—Varicolored, brown (predominant), reddish-brown to black stained clasts, iron oxyhydroxide-cemented deposits. Textures are similar to colluvial ferricrete described above; however, manganese is in sufficient abundance to cause outcrop matrix and clast coatings to have a brown to black color. The term transitional is used to describe those deposits that are observed to have a mixed manganocrete and ferricrete composition. Deposits are preserved in Placer Gulch. Thickness 0.5 to 3 m

bi — **Bog iron deposits (late Pleistocene to modern)**—Very fine grained, iron oxyhydroxysulfate deposits consisting of goethite, jarosite, and schwertmannite; varicolored, brown (predominant), reddish-brown to brownish-yellow with black-stained partings. Unit is commonly well indurated and thin bedded but may be moderately indurated and porous. Locally, alternating dark-reddish-brown and brownish-yellow lamina occur, and locally beds are crosscut by fractures filled with laminated bog iron. A finely filamentous texture occurs in some outcrops, which appears to be similar to textures observed in active iron bogs. Iron compound casts of roots and conifer needles occur locally. Unit in many places grades laterally and (or) vertically into clastic alluvial or colluvial ferricrete. Bog iron deposits may be water saturated but are predominantly dry at present. Dry bog iron deposits were once active iron-rich springs, which precipitated and deposited iron oxyhydroxides adjacent to them. Wet, active iron-rich springs such as the spring near the confluence of Middle Fork and Mineral Creek have deposited a terraced mound. Wood fragments encased in bog iron deposits have ^{14}C ages ranging from 380 to 4,010 yr B.P. Outcrop thickness ranges from 1 to 5 m; maximum thickness unknown

99ABFC170 — Sample site (see this volume, Chapters E14–E17)

F7 — Photograph location, figures 2–15

Figure 9. Alluvial manganocrete near the former Lake Emma in Eureka Gulch. Photo on left shows black, manganese-stained, crudely bedded paleo-alluvial fan deposit. Photo on right is closeup view of stratigraphy.

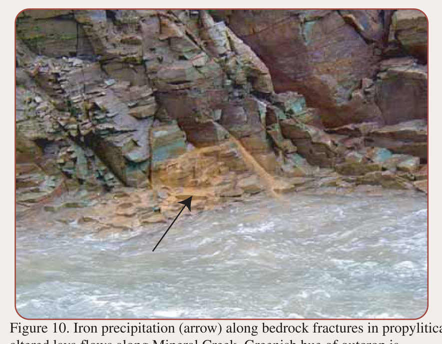


Figure 10. Iron precipitation (arrow) along bedrock fractures in propylitically altered lava flows along Mineral Creek. Greenish hue of outcrop is characteristic of the propylitic mineral assemblage that includes chlorite-epidote-calcite-quartz-pyrite-iron oxides. Iron precipitation here and elsewhere is an indication of acidic conditions upstream caused by pyrite oxidation. Ferricrete forms where such iron precipitation occurs in contact with porous surficial deposits.

Figure 11. Colluvial ferricrete crosscut by vertically layered bog iron, above South Fork Cement Creek (view to east).

Figure 12. Colluvial ferricrete above South Fork Cement Creek, deposited on a hillslope topographically below altered lavas (upper right). View to east.

Figure 13. Bog iron outcrop near headwater region of Topeka Gulch. Deposit is essentially clast free and consists of fine, horizontally laminated iron oxyhydroxide (goethite). Vertically laminated bog iron deposits also crop out in upper Animas River watershed (fig. 11). Bog iron deposits are inactive, and are likely the remnants of once active iron springs and iron bogs.

Figure 14. Iron bog located east of Dry Gulch along Cement Creek. Iron bogs are shallow mixing zones, having at this site a range of pH (3.2 - 5.7) and conductivity (900 - 1,700 microsiemens per centimeter) values. Oxidation of ferrous iron and mixing of ground water result in precipitation of iron trapped in pools or in organic material. Iron bogs are often transitional to sedge bogs.

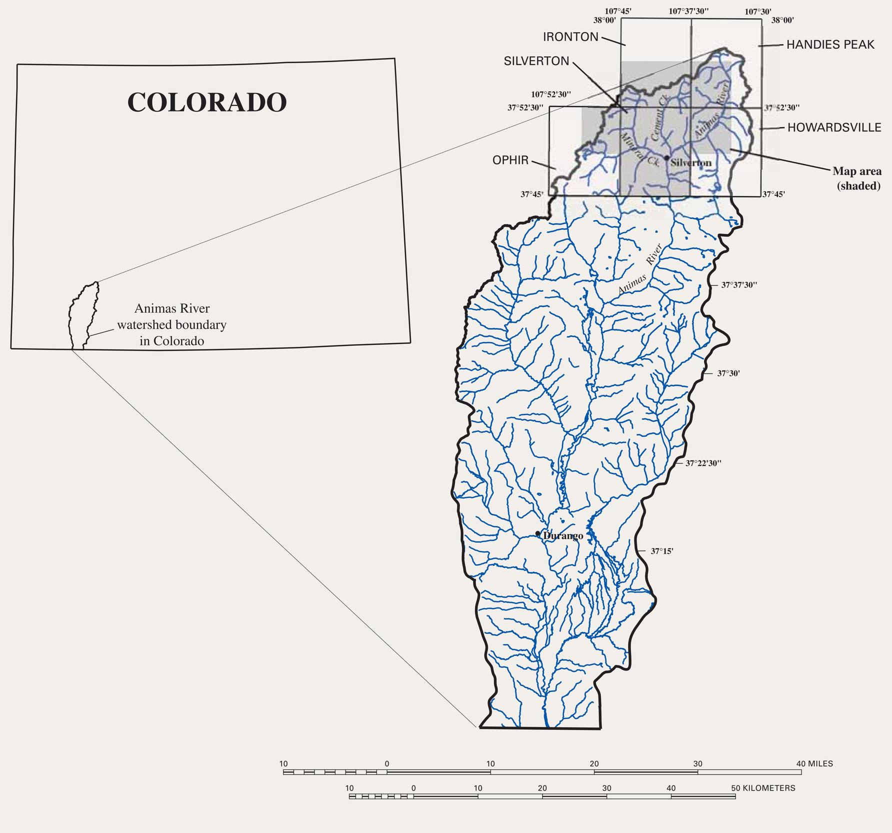


Figure 1. Index map of Animas River watershed.

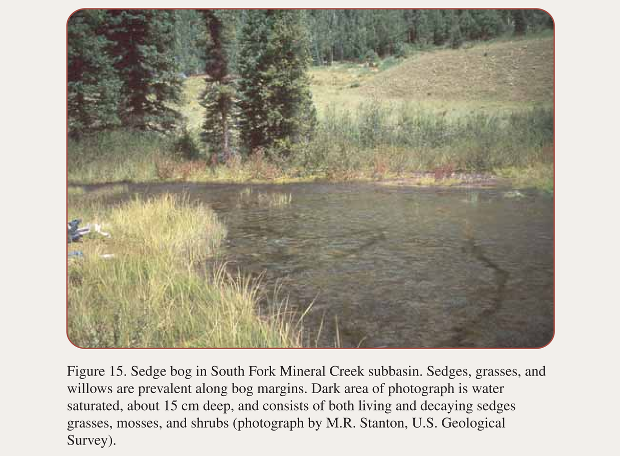


Figure 15. Sedge bog in South Fork Mineral Creek subbasin. Sedges, grasses, and willows are prevalent along bog margins. Dark area of photograph is water saturated, about 15 cm deep, and consists of both living and decaying sedges grasses, mosses, and shrubs (photograph by M.R. Stanton, U.S. Geological Survey).

PROJECT DESCRIPTION AND STUDY AREA

During 1996–2000, the Bureau of Land Management, National Park Service, Environmental Protection Agency, United States Department of Agriculture (USDA) Forest Service, and the U.S. Geological Survey (USGS) developed a coordinated strategy to (1) study the environmental effects of historical mining on Federal lands, and (2) remediate contaminated sites that have the greatest impact on water quality and ecosystem health. The focus of our involvement in this study was to develop a methodology to identify and characterize watersheds that are most at risk for environmental degradation caused by historical mining. A watershed scale of observation was utilized because most of the riparian ecosystem of the upper Animas River watershed study area (fig. 1) is affected by historical mining lasting more than a century. The Animas River watershed was chosen for study in large part because of the hundreds of inactive mines and prospects scattered throughout the watershed.

One important objective of our USGS Abandoned Mine Lands Initiative was to estimate the premining geochemical baseline conditions in the Animas River watershed because an understanding of this characteristic is needed to establish achievable restoration goals. Ferricretes (stratified iron- and manganese-oxyhydroxide-cemented sedimentary deposits) are one indicator of the geochemical baseline conditions as well as the effect that weathering of mineralized rocks had on water quality in the Animas River watershed prior to mining. The term ferricrete was first used by Lamplugh (1902) to describe iron-cemented surficial sand and gravels that formed by precipitation of infiltrating solutions of "iron salts." Ferricretes occur in several mining districts throughout the western United States. They have been used as an exploration tool by miners and previous researchers because of their high trace-element abundances (Wirt and others, this volume, Chapter E17) and as an indicator of paleo-weathering conditions (Battiau-Queney, 1996). Ransome (1901) suggested that ferricretes in the upper Animas River area form at springs where iron precipitates from acidic, iron-rich meteoric ground water as it reacts with the atmosphere and becomes oxidized. The acidic ground water is thought to have resulted from weathering of sulfides and other acid-generating minerals disseminated in altered bedrock (Ransome, 1901). Plumlee and others (1995), in studies of acid-sulfate mineralization and associated ferricrete deposits at Summitville, Colo., presented similar conclusions to those of Ransome (1901) regarding ferricrete formation. Ferricrete deposits, which are thought to have formed under acidic conditions in streams, have also been investigated in the New World Mining District, Mont. (Furniss and Hinman, 1998; Furniss and others, 1999). Twenty-two radiocarbon ages determined for ferricrete-encased wood collected in the New World Mining District range from modern to 8,840 years B.P. (Furniss and Hinman, 1998; Furniss and others, 1999). Logs and wood fragments preserved in several ferricretes in the upper Animas River watershed, collected primarily along streams, yield radiocarbon ages of modern to 9,580 years B.P. (Verplanck and others, this volume, Chapter E15). Radiocarbon age ranges on wood collected from ferricrete in the study area overlap the range of post-deglaciation ages determined for wood fragments collected from tarn deposits at the head of Eureka Gulch, northeast of Silverton, Colo. (Carrara and others, 1984; Carrara and others, 1991; Elias and others, 1991). The presence of ferricrete deposits along the current stream courses indicates that climate and physiography of the Animas River watershed have been relatively constant throughout the Holocene and that weathering processes have been ongoing for thousands of years prior to mining activities. Thus, by knowing where ferricrete is preserved in the watershed today, land-management agencies have an indication of (1) where metal precipitation from weathering of altered rocks has occurred in the past and (2) where this process is ongoing and may confound remediation efforts.

We mapped the distribution of ferricretes and determined their physical properties as part of the Animas River watershed study, to build a spatial framework for observing the processes responsible for their formation and preservation, and to document the stability of the current weathering surface throughout the Holocene. The Animas River watershed study area, as defined for this study, is the drainage of three tributaries (Mineral and Cement Creeks, and the Animas River upstream from their confluence near Silverton, Colo.). It is ideally suited for such a detailed study of ferricrete occurrences because (1) the combined weathering, glacial, hydrologic, erosion, and deposition processes have preserved and exposed numerous ferricrete outcrops; (2) iron-rich and manganese-rich springs and seeps are abundant; (3) bedrock and surficial deposit exposures are excellent; and (4) ferricrete deposits occur near to both inactive mines and naturally occurring alteration zones found throughout the watershed.

MAP SUMMARY

This map shows the distribution of ferricrete, manganocrete, and iron bogs and springs in the upper Animas River watershed. The Mineral and Cement Creek basins were mapped in detail to delineate the extent and variation of ferricrete occurrences. However, the Animas River basin upstream of the town of Silverton was mapped at a reconnaissance level of detail. Field data were compiled on the Ironton, Handies Peak, Ophir, Silverton, and Howardsville 1:24,000 topographic maps and on ≈1:6,000 scale aerial photos of Cement Creek. All data were digitized with ARCEDIT and ERDAS IMAGINE software. Two coverages were created, including an active bogs coverage and a ferricrete coverage. Digital ortho quadrangles (DOQ, 1997, Universal Transverse Mercator projection, Zone 13, NAD27 datum) with a 1 m resolution were used as a back coverage when data were compiled and digitized from the topographic maps and aerial photos. The high-resolution DOQ base is required to depict typically thin alluvial deposits preserved in stream terraces along Mineral and Cement Creeks. MAPublisher was used to import the ArcInfo coverages and digital ortho quadrangles into Adobe Illustrator to produce the final map.

FIELD METHODS

Physical properties were recorded at each outcrop to create a classification scheme (Verplanck and others, this volume, Chapter E15). Important observations include clast presence or absence and degree of rounding, lithologies represented, grain size, sorting, matrix type, porosity, color, occurrence of small-scale structures, orientation of layering, and dimensions of outcrop. We also noted whether the outcrop was wet or dry to determine if the deposit was active or ancient, observing that seasonal or temporal variation in ground-water flow is not always a definitive determination of active or ancient. Five principal classes of these iron-cemented deposits were mapped:

1. bog iron, thinly bedded deposits with essentially no clasts and usually associated with active or paleo-springs
2. colluvial ferricrete, massive to crudely bedded deposits with angular clasts that are primarily monolithologic
3. alluvial ferricrete, massive to finely bedded deposits with rounded and commonly imbricated clasts
4. alluvial and colluvial manganocrete, deposits within the alluvial and colluvial class types that are very dark brown to black in outcrop owing to the presence of highly elevated concentrations of manganese and iron matrix cement
5. transitional ferricrete and manganocrete, compositionally transitional between manganocrete and ferricrete

DISTRIBUTION OF FERRICRETE DEPOSITS

Ferricrete deposits form in surficial deposits that are adjacent to or that overlie mineralized faults and veins and pervasively altered bedrock. Iron-rich springs are also deposition sites for ferricrete (bog iron type) when an active spring either becomes dry or migrates as iron precipitation causes spring surface flow to be diverted. At the 1:24,000 map scale, these deposits seem small and localized when compared to other mineralized deposits found throughout the entire Silverton caldera region. However, a distinct topologic relationship exists among the preservation of these deposits, Tertiary structures, mineralized bedrock, and acidic waters in streams and springs in the Silverton area.

Ferricrete is preserved as iron-cemented, paleo-to-modern alluvial terraces where highly altered rocks between the Middle Fork and South Fork of Mineral Creek coincide with the Silverton caldera structural margin. Mineralized and fractured rocks located along this ring fault upstream and adjacent to the Mineral Creek alluvial terraces (such as the Cu-Mo porphyry mineral deposit located between the Middle and South Forks of Mineral Creek (Ringrose, 1982; Yager and others, 2000)) appear to be an important source of iron-rich water. The acid-sulfate mineralized rocks of Red Mountain (Bove and others, this volume, Chapter E3) and likely related mineralization products on Anvil Mountain contribute to alluvial and colluvial ferricrete formation along much of Cement Creek. The effect of water seeping from weathered and mineralized zones is also observed in the coarse colluvial, mixed or transitional ferricrete plus manganocrete deposits that occur in Placer Gulch. These deposits overlie the northeast-trending Sunnyside fault where sulfide-rich polymetallic, base- and precious-metal veins delineate the north edge of the Eureka graben. The Eureka graben faults formed during late-stage caldera resurgence and doming about 27.7 Ma. Colluvial ferricrete is similarly observed in the North Fork of Cement Creek below the upper Gold King mine. These colluvial ferricrete deposits drape existing topography and overlie polymetallic veins that crosscut the North Fork of Cement Creek drainage.

Manganocrete crops out as fine-grained colluvial and alluvial deposits in drainage areas located downstream from weathered, manganese-rich, pyroxmangite [(Mn,Fe) SiO_3]- and rhodochrosite ($MnCO_3$)-bearing vein structures associated with the Eureka graben. California Gulch, Eureka Gulch, and Placer Gulch drain the northern region of the Eureka graben, near the northeast-trending Sunnyside fault. Alluvial fans and colluvium in the California, Eureka, and Placer Gulch valley floors provide porous and permeable pathways for transport and precipitation of the manganese-rich fluids derived from weathering of mineralized veins. The influence of mining cannot be ruled out in the formation of a colluvial manganocrete deposit that is mapped in the headwater regions of Eureka Gulch.

Active iron springs tend to form and bog iron deposits tend to accumulate in hanging valleys and creek bottoms where a combination of highly fractured and altered rocks and topographic relief provides nearly continuous ground-water flow. Inactive springs and bogs are typically perched along valley hillslopes.

Iron-cemented mine waste has a similar texture, color, and mode of formation as naturally occurring ferricrete and manganocrete. Although these mine waste deposits are generally too small to be included on this map, they are important to consider in the context of the types of deposits that may be preserved at mine waste sites. Although, by definition, iron- and manganese-cemented mine waste is technically not ferricrete or manganocrete (Lamplugh, 1902; Furniss and Hinman, 1998), these are surficial deposits that form where mine waste piles drain acid-mine waters, which eventually precipitate the iron or manganese cement. The best examples of iron-cemented mine waste occur at the Yukon tunnel east of Cement Creek near Illinois Gulch and at the Bonner mine, located south of the Middle Fork Mineral Creek.

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REFERENCES CITED

Battiau-Queney, Yvonne, 1996, A tentative classification of paleoweathering formations based on geomorphological criteria, *in* Bouchard, Mireille, and Schmitt, Jean-Michel, eds.: Geomorphology, v. 16, p. 87–102.

Carrara, P.E., Mode, W.N., Rubin, Meyer, and Robinson, S.W., 1984, Deglaciation and postglacial timberline in the San Juan Mountains, Colorado: Quaternary Research, v. 21, p. 42–55.

Carrara, P.E., Trimble, D.A., and Rubin, Meyer, 1991, Holocene treeline fluctuations in the northern San Juan mountains, Colorado, U.S.A., as indicated by radiocarbon-dated conifer wood: Arctic and Alpine Research, v. 23, no. 3, p. 233–246.

Elias, S.A., Carrara, P.E., Toolin, L.J., and Jull, A.J.T., 1991, Revised age of deglaciation of Lake Emma based on new radiocarbon and macrofossil analyses: Quaternary Research, v. 36, p. 307–321.

Furniss, George, and Hinman, N.W., 1998, Ferricrete provides record of natural acid drainage, New World District, Montana, *in* Arehart, G.B., and Hulston, J.R., eds., Water-rock interaction: Rotterdam, Netherlands, Balkema, p. 973–976.

Furniss, George, Hinman, N.W., Doyle, G.A., and Runnells, D.D., 1999, Radiocarbon-dated ferricrete provides a record of natural acid rock drainage and paleoclimatic changes: Environmental Geology, v. 37, p. 102–106.

Lamplugh, G.W., 1902, Calcrete: Geological Magazine, v. 9, p. 575.

Plumlee, G.S., Gray, J.E., Roeber, M.M., Jr., Coolbaugh, Mark, Flohr, Marta, and Whitney, Gene, 1995, The importance of geology in understanding and remediating environmental problems at Summitville, *in* Posey, H.H., Pendleton, J.A., and Van Zyl, Dirk, eds., Proceedings; Summitville Forum '95: Colorado Geological Survey Special Publication 38, p. 13–22.

Ransome, F.L., 1901, A report on the economic geology of the Silverton quadrangle: U.S. Geological Survey Bulletin 182, 265 p.

Ringrose, C.R., 1982, Geology, geochemistry, and stable isotope studies of a porphyry-style hydrothermal system, west Silverton district, San Juan Mountains, Colorado: Aberdeen, Scotland, University of Aberdeen Ph. D. dissertation, 257 p.

Yager, D.B., Mast, M.A., Verplanck, P.L., Bove, D.J., Wright, W.G., and Hageman, P.L., 2000, Natural versus mining-related water quality degradation to tributaries draining Mount Moly, Silverton, Colo., *in* Proceedings of the Fifth International Conference on Acid Rock Drainage, Volume 1: Littleton, Colo., Society for Mining, Metallurgy, and Exploration, Inc., p. 535–547.