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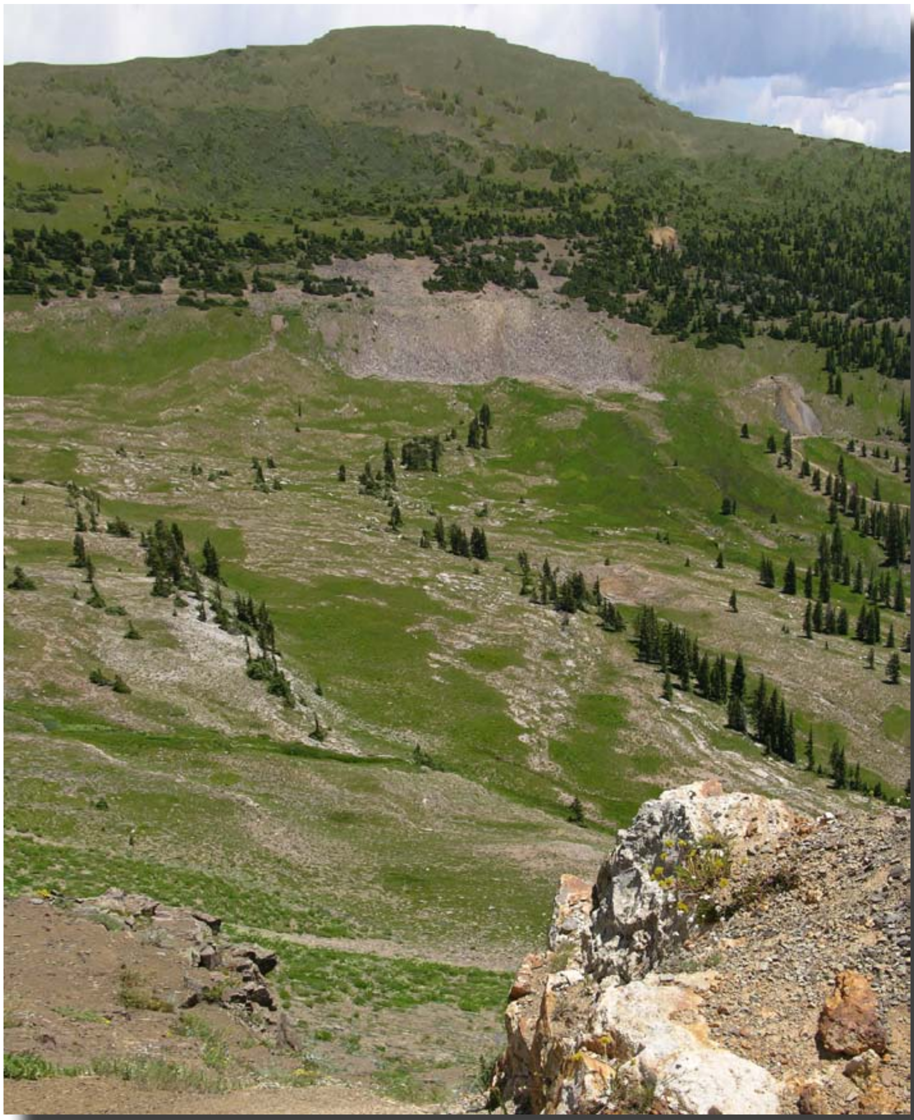
Characterization of Geologic Structures and Host Rock Properties Relevant to the Hydrogeology of the Standard Mine in Elk Basin, Gunnison County, Colorado



Open-File Report 2010–1008

U.S. Department of the Interior
U.S. Geological Survey

Front cover: Photograph of upper Elk Basin looking east from the cirque ridge.

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KEN SALAZAR, Secretary

U.S. Geological Survey
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Conversion Factors

SI to English Customary Units

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft.)
kilometer (km)	0.6214	mile (mi.)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2.)
	Volume	
liter (L)	0.2642	gallon (gal.)

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

°F=(1.8×°C)+32

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88). Elevation, as used in this report, refers to distance above the vertical datum. Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83) or the World Geodetic System 1984 (WGS 84).

Characterization of Geologic Structures and Host Rock Properties Relevant to the Hydrogeology of the Standard Mine in Elk Basin, Gunnison County, Colorado

By Jonathan Saul Caine, Andrew H. Manning, Byron R. Berger, Yannick Kremer, Mario A. Guzman, Dennis D. Eberl, and Kathryn Schuller

Abstract

The Standard Mine Superfund Site is a source of mine drainage and associated heavy metal contamination of surface and groundwaters. The site contains Tertiary polymetallic quartz veins and fault zones that host precious and base metal sulfide mineralization common in Colorado. To assist the U.S. Environmental Protection Agency in its effort to remediate mine-related contamination, we characterized geologic structures, host rocks, and their potential hydraulic properties to better understand the sources of contaminants and the local hydrogeology. Real time kinematic and handheld global positioning systems were used to locate and map precisely the geometry of the surface traces of structures and mine-related features, such as portals. New reconnaissance geologic mapping, field and x-ray diffraction mineralogy, rock sample collection, thin-section analysis, and elemental geochemical analysis were completed to characterize hydrothermal alteration, mineralization, and subsequent leaching of metallic phases. Surface and subsurface observations, fault vein and fracture network characterization, borehole geophysical logging, and mercury injection capillary entry pressure data were used to document potential controls on the hydrologic system.

Key observations include:

1. Polymetallic quartz veins and a fault zone are collocated with most of the Standard Mine workings; the fault cuts the veins and has a clay-rich core.
2. Localized and concentrated polymetallic sulfide vein mineral deposition is associated with the Standard and Elk fault veins in contrast to pervasive and disseminated pyrite deposition found in the surrounding host rocks.
3. Pervasive, iron-oxide stained, heterogeneously distributed, and open joint networks were observed in all rocks except the clay-rich fault gouge.
4. Discrete and asymmetric groundwater flow, primarily on the footwall side of the Standard fault vein, is associated with deposition of localized flowstone.
5. Preferential leaching of pyrite in surface exposures was observed in the footwall Upper Cretaceous Ohio Creek Member of Mesaverde Formation as compared with Tertiary Wasatch Formation in the hanging wall that did not show such leaching.
6. Mercury-injection permeametry indicates relatively high intergranular porosity and permeability in the Ohio Creek Member versus clay-rich gouge and the Wasatch Formation.

Observations, data, and hypotheses lead to a conceptual model where:

1. The Standard and possibly the Elk fault veins are the primary sources of solutes in the surface and groundwater flow systems.
2. Given the relatively low intergranular porosity and permeability of the host rocks, the heterogeneously distributed but relatively high-permeability iron-oxide stained joint networks are likely the major control on infiltration and groundwater flow in the subsurface.
3. The juxtaposition of possibly lower porosity and permeability Tertiary Wasatch Formation against the Upper Cretaceous Ohio Creek Member along the Standard fault vein, in combination with relatively low permeability, clay-rich fault gouge in the core of the fault, likely controls the occurrence and flow of water in the vicinity of the fault vein and in the mine workings.
4. Given the character of joint networks, fault-related rocks, sedimentary juxtaposition, the geomorphology of the watershed, and the potential variation in surface versus subsurface hydraulic gradients relative to the orientation of Standard fault vein, it appears that the structure probably does not act as a simple conduit allowing near-surface groundwater to drain directly downward into the mine workings.

The fault vein appears to act as an asymmetric, combined conduit-barrier to groundwater flow, and groundwater likely flows from the surface to the mine workings within joint networks distributed throughout the greater volume of the sedimentary bedrock in the upper Elk Basin. Once within the workings, water freely flows from higher to lower levels by way of raises and stopes and ultimately discharges at the various mine portals.

Introduction

The Standard Mine in the upper Elk Creek Basin, near Crested Butte, Colorado, was a precious- and base-metal mine initially established in the late nineteenth century (fig. 1). The deposit was mined intermittently from about 1880 through the mid-1960s (Wood and Oerter, 2007). The Standard, Micawber, Elk, and several other mineral deposits and occurrences in the upper Elk Basin are part of a regional network of epithermal, polymetallic quartz veins likely associated with Oligocene to Miocene intrusive activity in west-central Colorado (compare Gaskill and others, 1967; Obradovich and others, 1969; Thomas and Galey, 1982; Ludington and Ellis, 1983). The primary metals mined from the upper Elk Basin were silver, copper, lead, and zinc that were associated with many common sulfide minerals such as galena, sphalerite, chalcopyrite, and pyrite (Wood and Oerter, 2007).

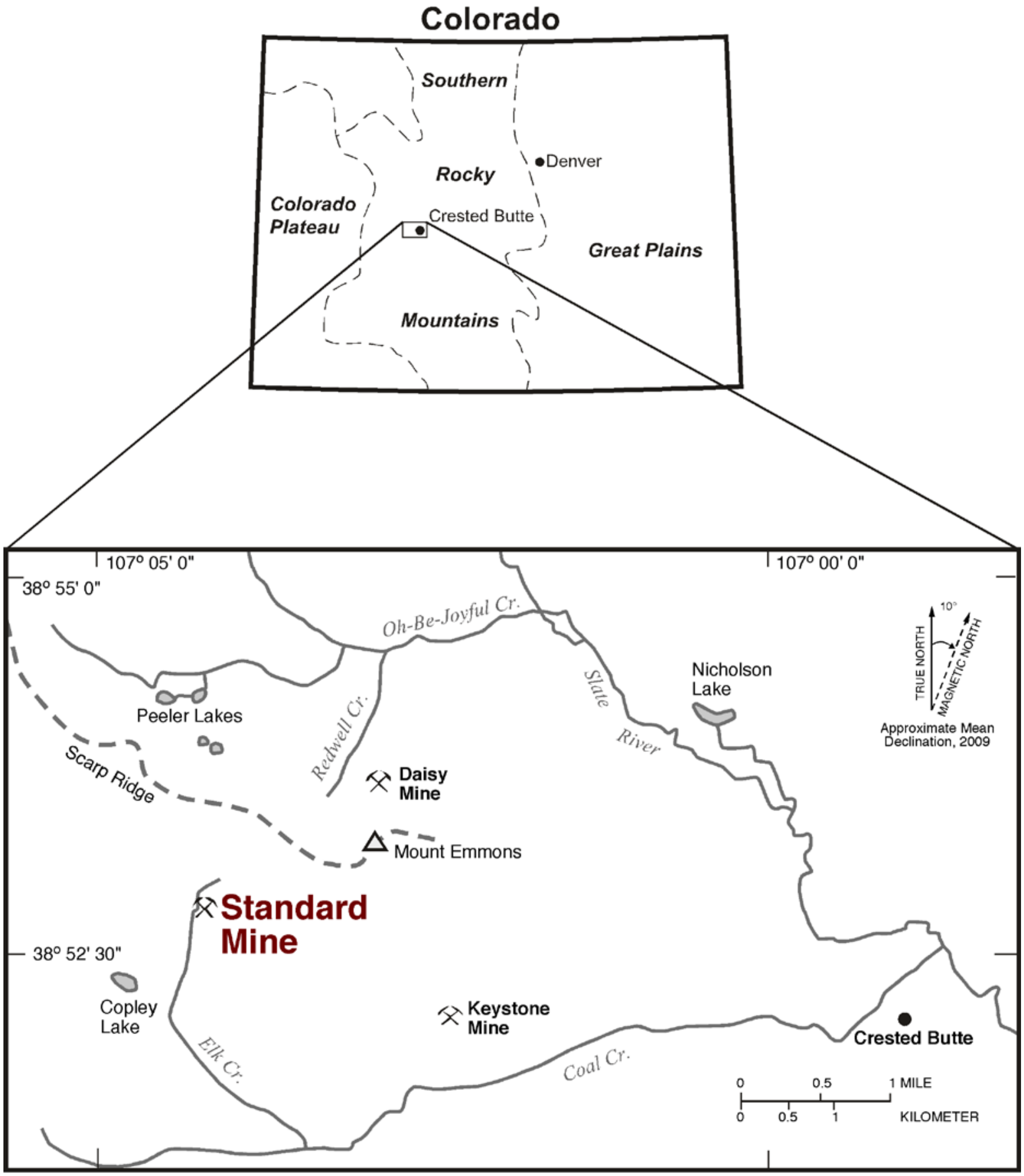


Figure 1. Location maps for the Standard Mine in the regional physiographic setting and local geographic setting.

Throughout the intermountain west, metalliferous mineral deposits such as those found in the upper Elk Basin have caused both natural and mining-related surface and groundwater contamination. Because of mine-related contamination, the Standard Mine and the upper part of the Elk Creek watershed have been listed by U.S. Environmental Protection Agency (USEPA) as one of about 27 Superfund sites in Colorado (EPA, 2009). Elk Creek is a tributary to Coal Creek, which is a source of domestic water for the town of Crested Butte. The Standard Mine drainage contributes dissolved and suspended concentrations of zinc, cadmium, lead, copper, and other metals into Elk Creek (Manning and others, 2007; Wood and Oerter, 2007; EPA, 2009). Although many abandoned mines, adits, and prospects are found within and adjacent to the Elk Creek watershed, the Standard Mine is one of the few that continually drains significant amounts of water. The Standard Mine has thus become a concern of local citizens, downstream users, and the USEPA. This report discusses geological and borehole geophysical data and observations collected in a continued effort to assist the USEPA in characterizing the geology of the upper Elk Basin and its surface and groundwater flow systems (figs. 2, 3). The focus is primarily on the physical characteristics of the Standard fault vein, related mine workings, and surrounding bedrock. Definitions of the structural components of faults and fault veins are provided in the context of how these features might affect groundwater storage and flow.

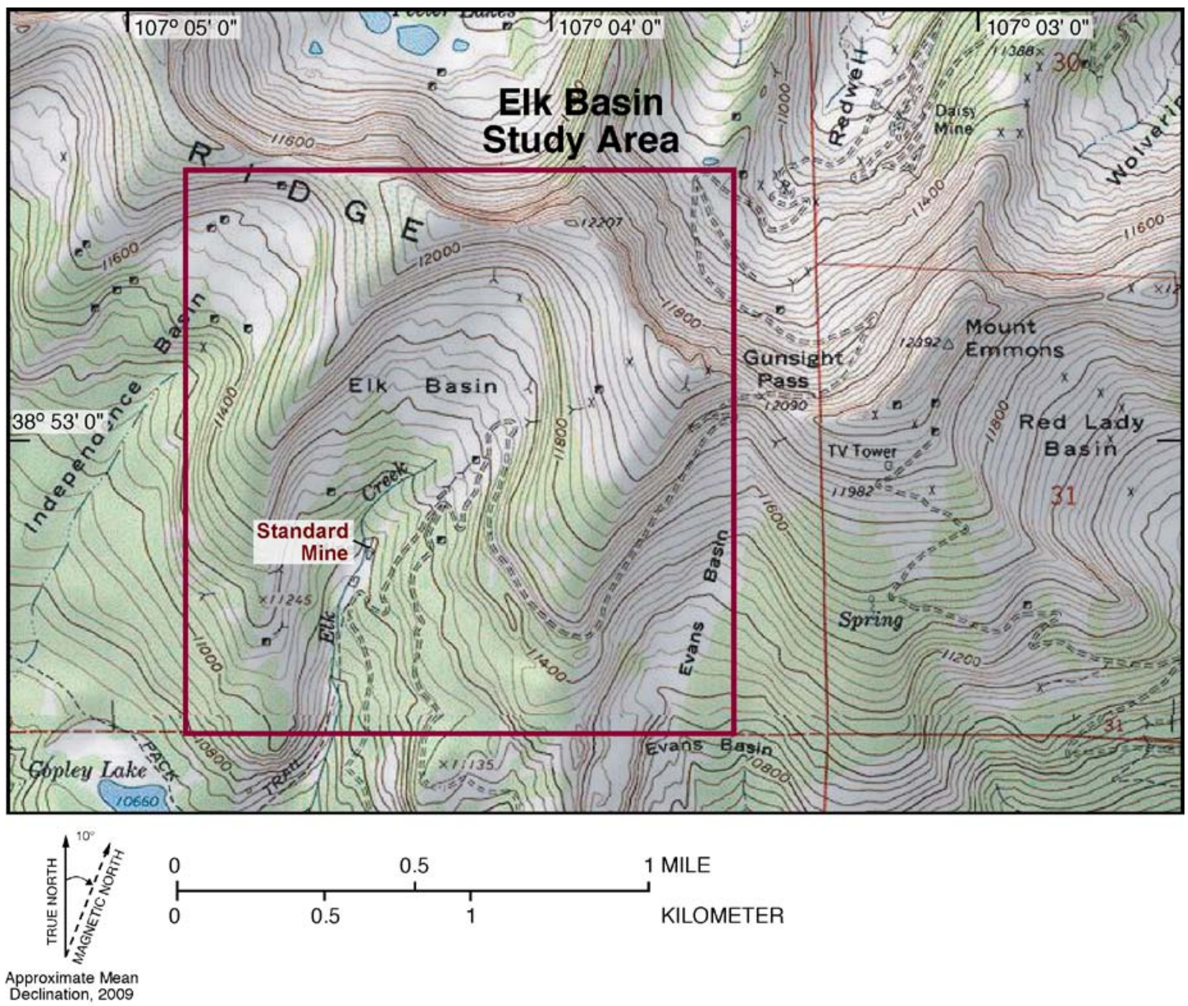
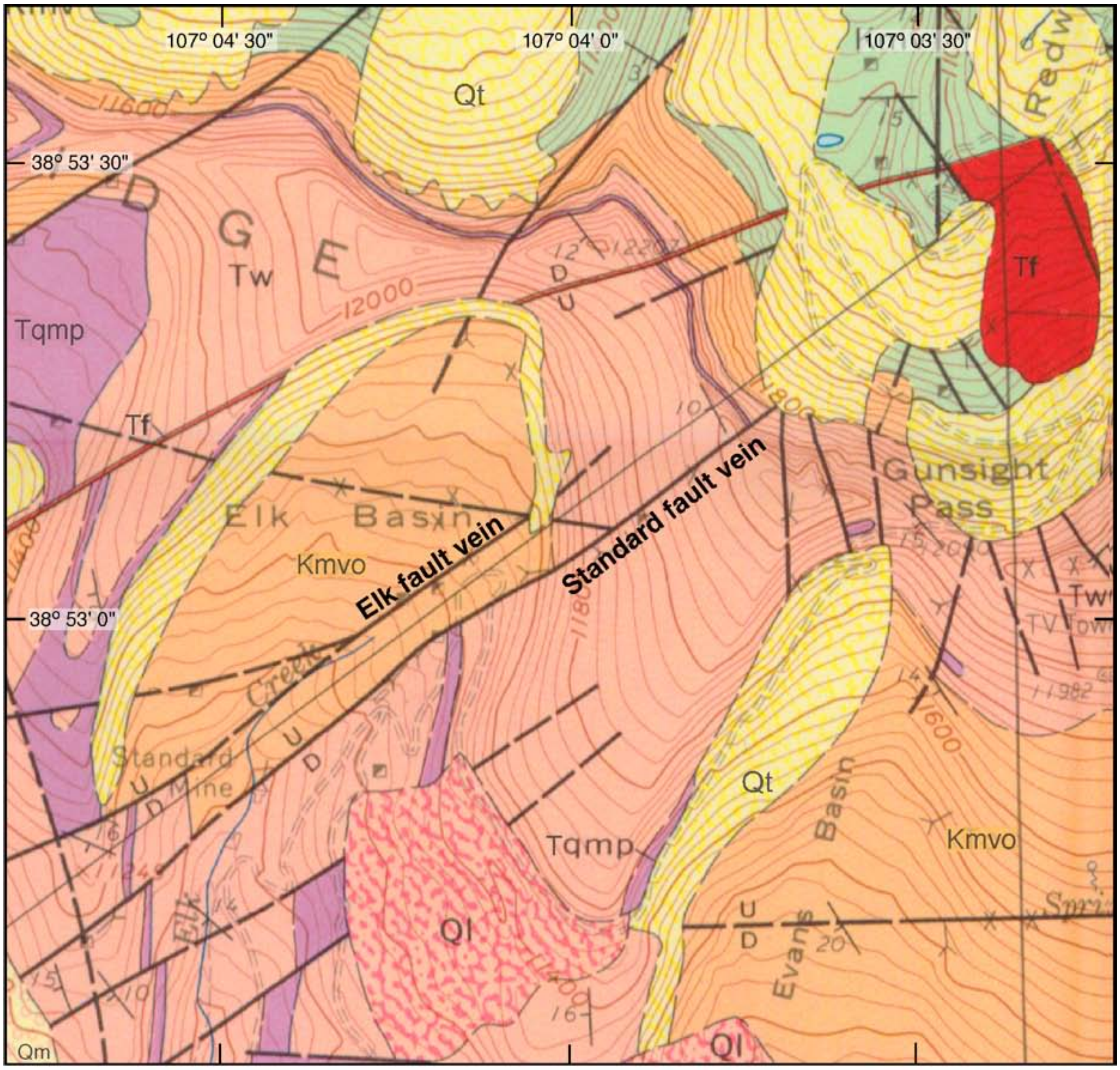
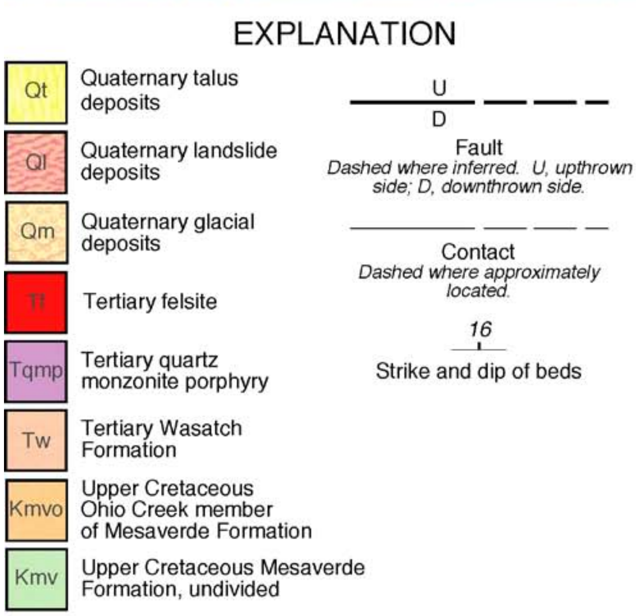


Figure 2. Part of the U.S. Geological Survey 1:24,000 scale topographic map showing the Elk Basin study area in the red box.





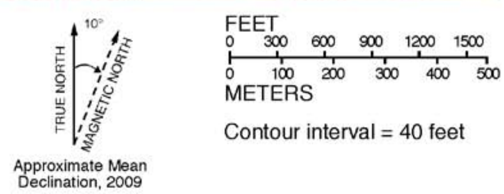


Figure 3. Part of the U.S. Geological Survey Oh-Be-Joyful quadrangle, Colorado geological map (1:24,000) showing the Elk Basin study area. Modified from Gaskill and others, 1967.

Also contained in this report are:

1. Surface and subsurface observations and measurements from two mine tunnels where geologic structures associated with the Standard fault vein are exposed.
2. Reconnaissance geological mapping and field mineralogical characterization of the near-surface bedrock.
3. High-accuracy real time kinematic global positioning system (RTKGPS) and handheld GPS measurements of the precise locations of the Standard fault vein and other important faults and veins, tunnel portals, shafts, previously drilled groundwater monitoring wells, and of a series of representative samples collected from traverses across the faults, veins, and host rocks.
4. Results of borehole geophysical and drill core logging.
5. Intergranular petrophysical porosity and permeability estimates.
6. Description of petrographic thin sections from the sample set.
7. Raw elemental chemistry and quantitative mineralogy data from the sample set.

Although the nature of this report is primarily descriptive, some speculative hypotheses regarding the major geological controls of the surface and groundwater flow systems are provided. The work and report have been completed rapidly to help the USEPA in its consideration of various remediation strategies appropriate for mitigating mine-related drainage. An in-depth treatment of the groundwater and surface water occurrence and geochemistry, various environmental issues, and key references related to the Standard Mine and upper Elk Basin can be found in Manning and others (2007). This report complements two other concurrent U.S. Geological Survey (USGS) reports on the Standard Mine site that present aqueous geochemistry data for mine waters and surface geophysical data (Minsley and others, 2010; Verplanck and others, 2010).

Definitions of Brittle Structures

Much of the surface and groundwater hydrologic system in Elk Basin appears to be controlled by brittle structures (Manning and others, 2007). In the interest of characterizing these structures in detail and to better understand their potential hydraulic influences, a series of definitions are provided along with a detailed figure depicting these structures (fig. 4). The term fracture is nongenetic and simply refers to a crack. Joints are opening-mode fractures in which the direction of movement of the two subparallel walls is perpendicular to one another (fig. 4). Faults are shearing-mode fractures where the walls slide past one another in directions other than perpendicular to one another. Although a shear fracture can open for an instant, the effect of shearing tends to grind wall-rock materials, which effectively closes the structure. A vein is simply a fracture, whether a joint or fault, that is filled with a mineral precipitate. Veins can also have openings within them referred to as vugs. If a vein has accommodated shear, it is referred to as a fault vein.

Fault zones are complex networks of shear- and opening-mode structures, and they commonly contain veins. Fault zones have distinctive components that impart structural, lithological, hydrological, and mechanical heterogeneity into a rock mass (Caine and others, 1996). Components include a fault core where most of the strain has been accommodated and where fault rocks such as gouge or fault breccia form (fig. 4). Fault cores are commonly surrounded by and are in sharp contact with a damage zone that is related to the growth of the fault and is composed of networks of small faults, joints, veins, and folds (Chester and Logan, 1986). The contact between a fault core and damage zone is commonly a polished and striated slip surface that can be heterogeneously open or closed. These fault components are surrounded by the protolith or relatively undeformed host rocks.

Because fault cores are commonly composed of clay-rich gouge or crushed and cemented rock, they can have permeability that is orders of magnitude lower than that of the surrounding rocks, thus forming a barrier to groundwater flow. However, some fault zones are composed primarily of networks of open joints with higher permeability than is found in the surrounding rock, causing the fault to be a conduit to flow. Most commonly, fault zones have a core and damage zone that can cause the fault to be both a conduit and a barrier to flow—impeding flow across the fault and enhancing flow parallel to it, depending on the orientation of the hydraulic gradient relative to the orientation of the fault zone (Caine and Forster, 1999). Fault zones can also have internal heterogeneity with multiple cores or poorly developed damage zones (or both). Fault veins can be quite complex with extremely low permeability, massive veins adjacent to clay-rich fault cores, pods of damaged rock, slip surfaces, and fracture networks sandwiched between the veins and gouge. These structures may cause complex baffling and rerouting of groundwater flow that interacts with fault veins (fig. 4).

Site Description

Location, Ecosystem, and Climate

The Standard Mine is located in the upper Elk Creek watershed (Elk Basin) in the Ruby Range between the Elk and West Elk mountains, about 6 kilometers (km) west-northwest of the town of Crested Butte, Colorado (fig. 1). The watershed is in an alpine setting at about 3,290 to 3,720 meters (m) above sea level. Topographic gradients range from 0.2 to 0.6 and the watershed is approximately 2.6 km^2 in size (fig. 2). Elk Basin is drained by the perennial Elk Creek that enters Coal Creek at the mouth of the watershed. The soils and surficial deposits are thin yet rich in organic matter and there is Tertiary sedimentary bedrock at or near the surface in most of the upper

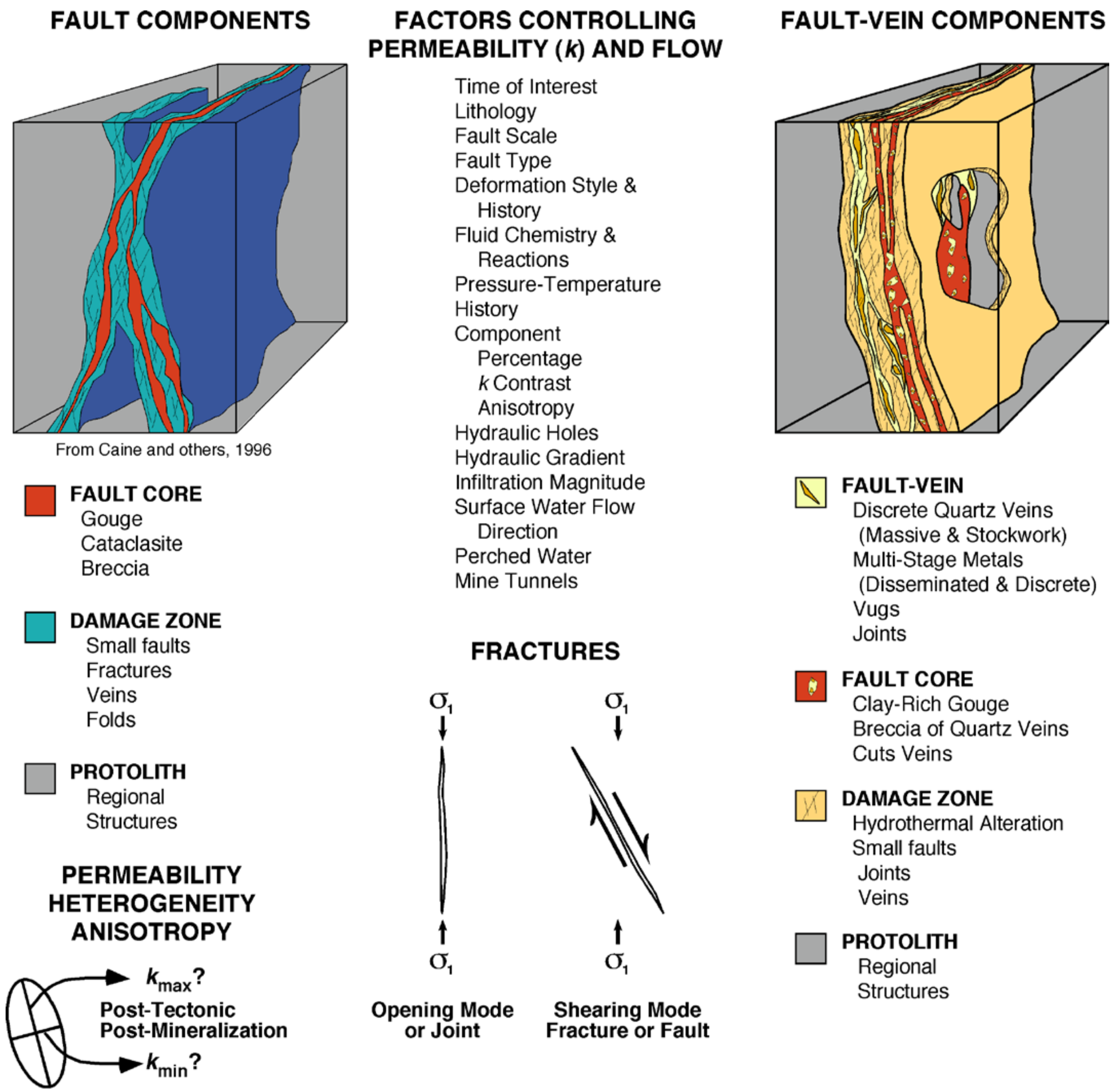


Figure 4. Fault zone, fracture, and fault vein conceptual models showing physical components and potential hydrological influences. The ellipse depicts the possible directions of maximum and minimum permeability for a fault or fault vein after they have formed causing them to be complex conduit-barrier systems. A sketch of the basic types of fractures found in nature with the ideal maximum principal stress (σ_1) orientation that controls their formation is also shown.

watershed. Conifers dominate the vegetation which includes mixed spruce and fir in the forest and subalpine tundra that covers much of the upper basin floor (fig. 5). Fauna are typical of subalpine environments in central Colorado and include larger mammals such as deer, elk, black bear, and mountain lions. Data from nearby meteorological stations indicate that Elk Basin has a mean annual air temperature of about 1°C and mean annual precipitation of about 79 centimeters per year (cm/yr), approximately 65 percent of which is snow that typically covers the basin from November through May (Manning and others, 2007).

Geological and Hydrological Overview

Elk Basin is underlain by Upper Cretaceous and Tertiary fluvial-lacustrine sedimentary rocks (fig. 3). During the Oligocene, a series of intermediate composition sills and dikes intruded the sediments followed by intrusion of a Miocene felsic rhyolite plug and associated dikes in the Mount Emmons area (Gaskill and others, 1967; Obradovich and others, 1969; Thomas and Galey, 1982). Polymetallic mineral deposits and pervasive disseminated base metal mineralization are associated with these intrusive episodes (Ludington and Ellis, 1983).

Figure 5. Photograph of upper Elk Basin looking east from the cirque ridge. The white rocks at the center base of the photo are part of a fault vein mapped by Gaskill and others (1967). Stratigraphic and geomorphic benches can be seen on the floor of the cirque. The Level 5 portal and an upper adit of the Standard Mine can also be seen in the upper right hand side of the photo.

The younger Miocene and felsic intrusive activity just outside of Elk Basin is associated with significant molybdenum deposits not found in any comparable abundance within mines of Elk Basin (Sharp, 1978; Thomas and Galey, 1982). Intrusive activity likely occurred at relatively shallow depths of less than 3 km and caused volumetrically extensive but generally weak hydrothermal alteration.

Geomorphologically, the upper Elk Basin is a cirque where other evidence for Quaternary glaciation and surface uplift includes abundant glacial polish and striations on many outcrop pavements. Numerous small springs exist in the upper basin (Manning and others, 2007); many of these feed small perennial and ephemeral low-order streams that ultimately flow into the main stem of Elk Creek. The Elk and Standard fault veins are important features as they are adjacent to the lowest order perennial and ephemeral stream channels and appear to have influenced formation of the backbone of the drainage network. Other than thin, organic-rich soils, surficial deposits in Elk Basin are sparse but include a few small talus as well as some moraines and small landslide debris fields (fig. 3; Gaskill and others, 1967).

The Paleocene-Eocene Wasatch Formation (Tw) is at the top of the sedimentary sequence. It is a well-indurated and complex series of ferromagnesian-silicate-rich, fine- to coarse-grained sandstones, siltstones, and mudstones, with thick lenses of conglomerate at its base and intermittently dispersed throughout. Given the relatively high iron content in these rocks and their deposition in a reducing environment with abundant organic material, the rocks show a distinctive green color in outcrop. The Ohio Creek Member of the Mesaverde Formation (Kmvo) formed during the Late Cretaceous and underlies the Wasatch Formation (compare Gaskill and others, 1967; Johnson and May, 1980). The Ohio Creek is composed of moderately to poorly indurated, aluminosilicate-rich sandstones, siltstones, shales, and carbonaceous shales, with massive pebbly sandstones and conglomerates near its base. The rich organic content in the Ohio Creek Member indicates deposition in a reducing environment; however, the distinct lack of iron-rich phases results in a distinctive light-gray to beige color in many of the sand beds exposed in Elk Basin. Although not exposed in Elk Basin, the Wasatch and Ohio Creek are underlain by the Upper Cretaceous Mesaverde Formation (Kmv), which is composed of interbedded sandstone, shale, coal, and carbonaceous shale. The hydraulic properties such as porosity and permeability of these rocks are currently poorly defined. Also, the elevation of the water table, degree of confined versus unconfined conditions, the occurrence of localized perched groundwater, and the coincidence of topographic divides with groundwater divides are also poorly understood in the watershed.

Geological structures in Elk Basin include joints, faults, veins, fault veins, dikes, sedimentary structures, and tilted sedimentary strata. These features, discussed below, may to one degree or another control and act as hydrological heterogeneities in the near surface and subsurface affecting the infiltration, storage, and flow of groundwater. Structural deformation, igneous activity, and metallic mineralization in the region were formed as part of a complex series of tectonic events associated with the Laramide orogeny, its waning stages, and possibly also with Rio Grande rifting to the south and east (compare Coogan and others, 2005). Although there are no absolute age constraints on the structures specifically in Elk Basin, Thomas and Galey (1982) point out that the Standard vein is part of a set of structures, including the Daisy and Keystone veins, that have radial symmetry about the rhyolite plug at Mount Emmons. This plug is associated with an 18–16 Ma granite porphyry stock underlying the area (Sharp, 1978). Thomas and Galey (1982) also hypothesized that because igneous rocks have not intruded the faults, the faults did not predate or control the emplacement of the stock and associated mineralizing fluids. Although the radial symmetry of these veins is consistent with this hypothesis, there are a number of crosscutting age relationships between joints, faults, veins, dikes, and other features that complicate a simple hypothesis for which further discussion is beyond the scope of this report.

Methods

Reconnaissance Geologic Mapping

In order to characterize the geologic structures in Elk Basin, characterization of the host rocks within which they reside was needed. Additionally, the precise locations of the Standard and Elk fault veins, mine portals, adits, and other structures were also requested by the USEPA. Thus, a few days of field time were spent completing reconnaissance mapping and position determinations using a handheld GPS and RTKGPS (table 1, fig. 6). Figure 7 is a revised geological map of the study area resulting from this effort. The RTKGPS data were acquired using a Leica GPS1200 base station set up at a central location. Raw observational data were converted to receiver independent exchange (RINEX) format and submitted to the National Geodetic Survey's (NGS) Online Positioning User Service (OPUS) to determine the precise location, including elevation. Roving GPS data from a receiver were corrected based on the OPUS base station location solution, with overall positional accuracies on the order of 5 to 10 cm.

Paper topographic and geologic basemaps were enlarged to approximately 1:6,000 scale and locations and map data were plotted directly on the maps. A handheld GPS with digital copies of the maps was used with the ArcPAD geographic information system (GIS). The accuracy of the handheld GPS is 2 to 5 m under ideal conditions. The RTKGPS was also used for collecting point-location data and establishing the accuracy of the handheld unit. The data from the handheld unit were generally within a few meters of locations also measured with the RTKGPS unit.

Table 1. Real Time Kinematic Global Positioning System Point Data for Boreholes, Standard and Elk Fault-Veins, and Mine Portals, Elk Basin, Colorado

[Abbreviations and notes: B = borehole, FLT = fault, , PNKFLG = pink flag, UTM = Universal Transverse Mercator, WGS84 = World Geodetic System of 1984, m = meters, E = east, N = north, amsl = above mean sea level, NAVD88 = North American Vertical Datum of 1988. Horizontal and vertical postions have been corrected using the National Geodetic Survey solution (http://www.ngs.noaa.gov/OPUS/) for base GPS station location]

Feature Name	Feature Description	UTM Position (WGS84, Zone 13)		Position Quality (m)	NAVD88 Elevation (m amsl)	Elevation Quality (m)
		mE	mN			
B1	Borehole	320532.08	4305778.07	0.24	3483.35	0.19
B2	Borehole	320531.97	4305782.18	0.24	3483.38	0.19
B3	Borehole	320534.91	4305871.69	0.11	3488.59	0.12
B4	Borehole	320475.85	4305748.79	0.09	3463.65	0.09
B5	Borehole	320443.16	4305716.89	0.09	3455.13	0.08
B6	Borehole	320446.20	4305708.78	0.09	3454.70	0.08
B7	Borehole	320475.63	4305845.16	0.24	3472.71	0.20
B8	Borehole	320303.04	4305653.08	0.11	3415.45	0.12
ELK	Benchmark above Elk Fault-Vein Portal	320417.48	4305959.06	0.24	3476.73	0.18
FLT-3	Standard Fault Trace near Level 3 Portal	320436.39	4305752.67	0.10	3455.75	0.10
FLT-4	Standard Fault Trace between Level 2 and 3 Portals	320314.17	4305648.10	0.09	3415.85	0.09
FLT-4B	Standard Fault Trace near Level 5 Portal	320358.37	4305685.70	0.09	3428.05	0.09
FLT-5	Standard Fault Trace near Level 1 Portal	320114.03	4305509.95	0.49	3354.15	0.93
PNKFLG	Standard Fault Trace near Level 5 Portal	320605.83	4305847.15	0.11	3507.95	0.12
FLT-6	Standard Fault Trace near SW fault tip	319943.61	4305371.61	0.84	3356.71	1.52
P1	Standard Mine Level 1 Portal	320122.42	4305516.06	0.10	3356.30	0.11
P3	Standard Mine Level 3 Portal	320449.86	4305757.98	0.11	3458.85	0.12
P4	Standard Mine Level 4 Portal	320478.97	4305785.17	0.24	3472.12	0.19
P5	Standard Mine Level 5 Portal	320666.97	4305940.66	0.11	3530.55	0.12

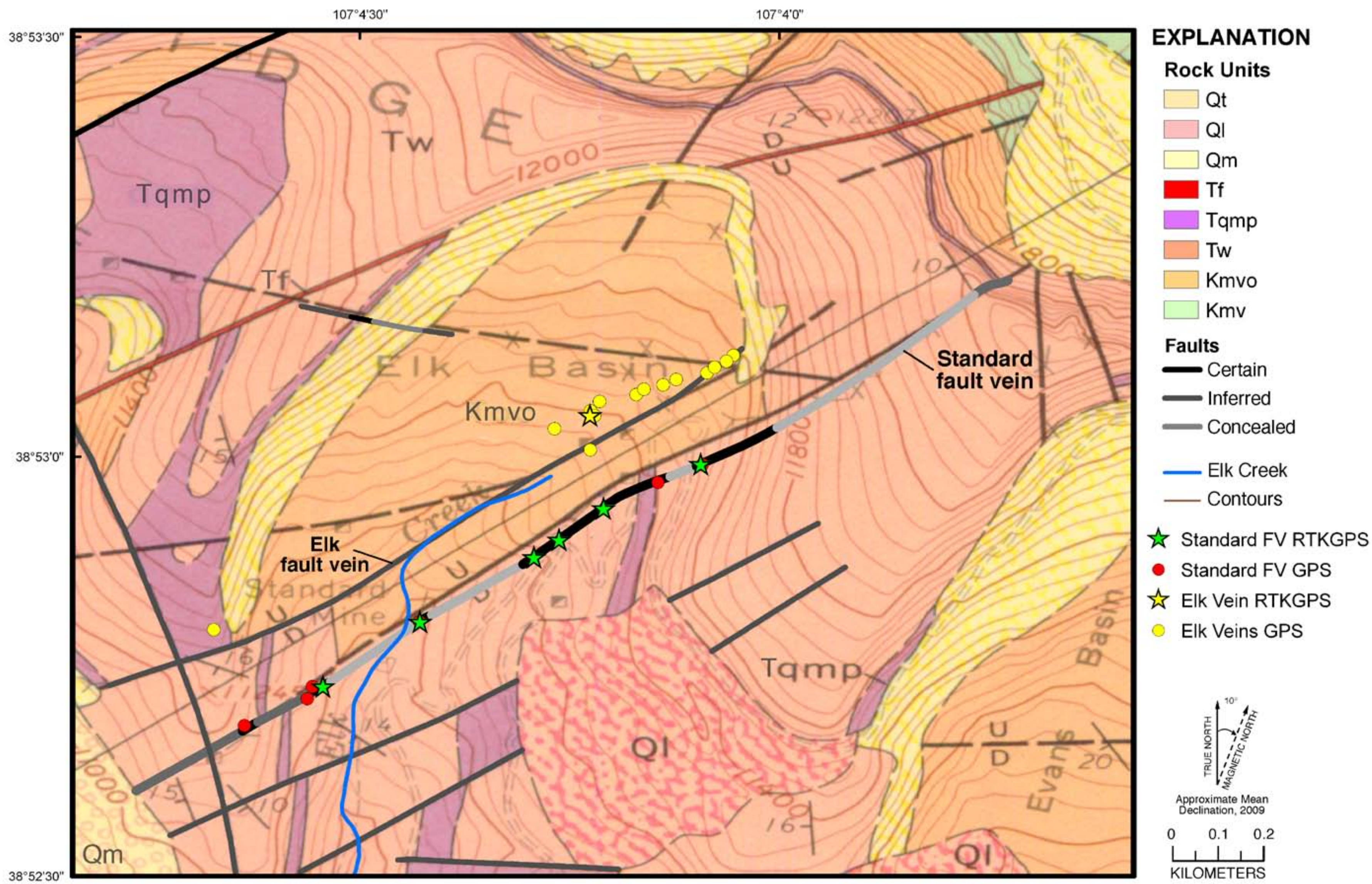


Figure 6. Gaskill and others (1967) geologic map (1:24,000) of upper Elk Basin overlain with the Real Time Kinematic and handheld GPS positions of the Standard and Elk fault veins. Qt, Quaternary talus deposits; Ql, Quaternary landslide deposits; Qm, Quaternary glacial deposits; Tf, Tertiary felsite; Tqmp, Tertiary quartz monzonite porphyry; Tw, Tertiary Wasatch Formation; Kmvo, Upper Cretaceous Ohio Creek Member of Mesaverde Formation; Kmv, Upper Cretaceous Mesaverde Formation; FV, fault vein; RTKGPS, real time kinematic global positioning system; GPS handheld global positioning system.

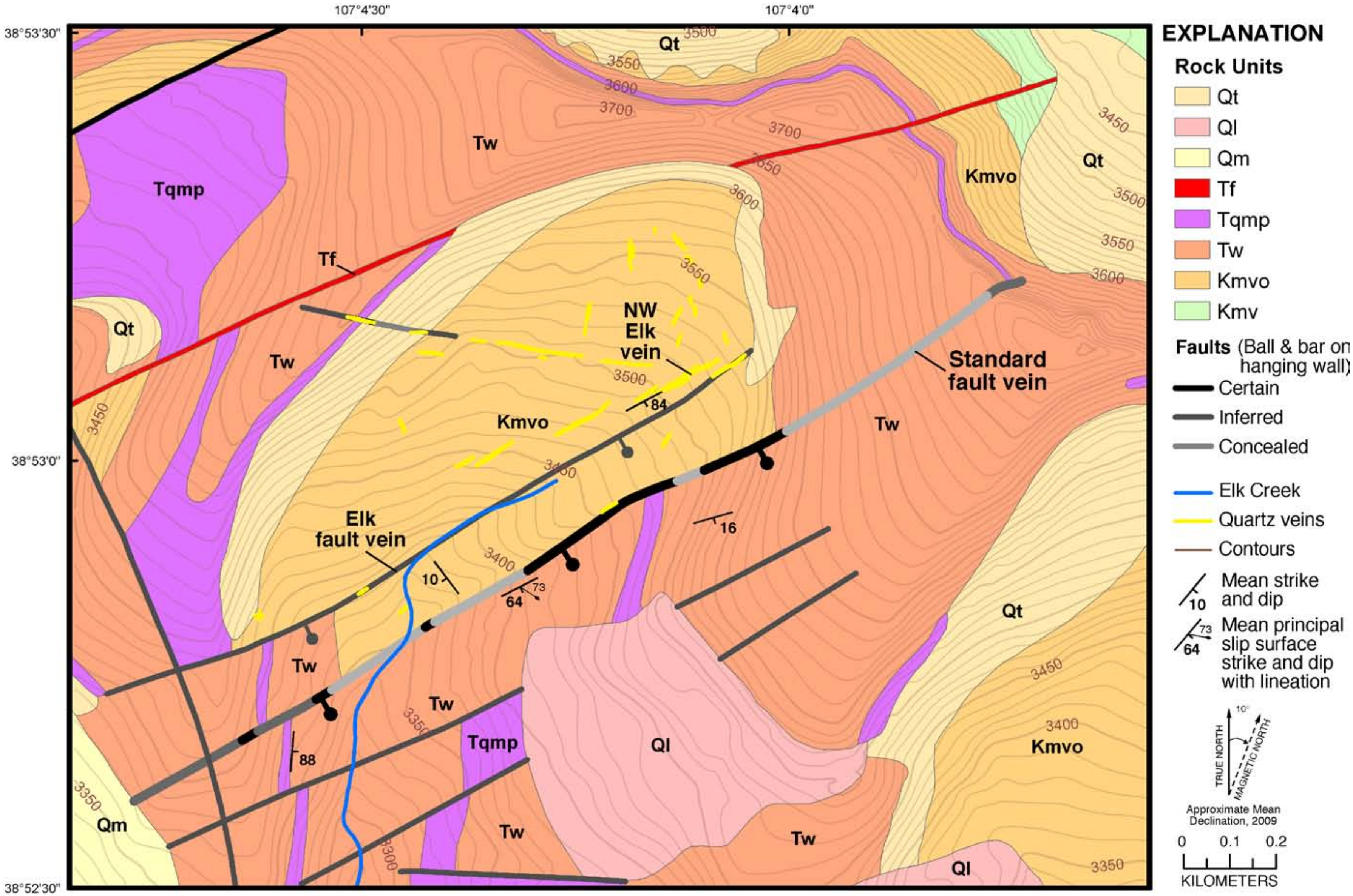


Figure 7. Reconnaissance geologic map of upper Elk Basin modified from Gaskill and others, 1967 revised by Jonathan Caine, 2009. Qt, Quaternary talus deposits; Ql, Quaternary landslide deposits; Qm, Quaternary glacial deposits; Tf, Tertiary felsite; Tqmp, Tertiary quartz monzonite porphyry; Tw, Tertiary Wasatch Formation; Kmvo, Upper Cretaceous Ohio Creek Member of Mesaverde Formation; Kmv, Upper Cretaceous Mesaverde Formation.

About 150 locations were visited in the upper Elk Basin. Lithostratigraphic unit, rock type, and basic mineralogy were recorded from hand samples freshly broken with a hammer and inspected with a hand lens at each location. Scratch tests, a magnet, and hydrochloric acid were used to aid mineral identification. The strike and dip of bedding, joints, faults, veins, dike margins, and other features were measured using a compass and inclinometer. The strike and dip of fault principal-slip surfaces and the rake of slip lineations in the plane of the slip surfaces were recorded. Shear sense was determined if possible from offset markers or slip-surface decorations and was graded as being certain, inferred, or uncertain. Where there were multiple features such as joints, numerous orientation measurements were recorded to obtain a representative sample of the distribution of the features. All orientation data were tabulated electronically in the field and later plotted on lower-hemisphere, equal-area projections using the computer program Stereonet (Allmendinger, 2004). Estimates of joint intensity, trace length, shape, and other properties were also noted where appropriate. The widths of features such as veins and faults were recoded using a tape measure. The locations of the Standard and Elk fault veins were determined by outcrop observation. In most instances, the position of the trace of the Standard fault at the surface was recognizable between outcrops of the Ohio Creek Member and Wasatch Formation to within about 3-m accuracy. A single point was selected between the outcrops and the position was recorded using the handheld GPS and RTKGPS. No locality was found where the core of the Standard fault vein was exposed at the surface; however, the primary quartz vein associated with the Standard fault was observed and mapped. The Elk fault vein is exposed in several localities and its position was recorded using the same methods as for the Standard. Many other quartz and polymetallic veins crop out in the Elk Basin, and these were also mapped using GPS.

Fault Zone Characterization

Characterization of a fault zone involves the observation and measurement of distinct structural and hydrologic components, such as a core and damage zone, if they exist in natural outcrops, road cuts, or mines. Tools such as a compass, inclinometer, and tape measure are used to collect orientation data on the strike and dip of the fault, associated slip surfaces and slickenline data, veins, fractures, bedding on either side of the fault, folds, and any other structures that may be associated with the fault. A detailed study of the fault core was completed at exposures ranging from less than 1 m to greater than 10 m in length. Direct measurement of along-strike and a few down-dip variations in fault core width were made using a tape measure. Estimates of fault displacement were made by using separation of Tertiary quartz monzonite porphyry (Tqmp) dikes and measurements of the principal slip surface and slickenlines at these locations. Fault displacement was estimated using the existing and revised geological maps where piercing points are present. Map inspection before fieldwork allowed the visitation of specific exposures near piercing points. Direct measurements of fault slip surfaces and slip lineation directions allowed for trigonometric computation of the net displacement along the fault. At one location in Level 5 of the Standard Mine the approximate contact between the Ohio Creek and Wasatch should have been at an elevation similar to that of the mine tunnel. This contact was not observed but the approximate location above the farthest northeast survey point in the tunnel was projected to the surface, at which point the known ground surface elevation yielded a minimum net displacement.

Twenty-two representative samples of each fault zone component were collected along traverses across the Standard fault vein, from drill core and throughout Elk Basin. Observations and analyses from the samples include:

1. Drill core logging of lithology, structures, alteration, and mineralogy (table 2).
2. Microstructural and petrographic characteristics from thin sections.
3. Three samples for mercury injection capillary pressure (MICP) determination of intergranular porosity and permeability (table 3).
4. Major and trace element composition (table 4).
5. Quantitative mineralogy (table 5).

Borehole Geophysical Logging

Several boreholes were drilled and completed as monitoring wells in association with the USEPA site-investigation activities. One of these, hole B8, was drilled to a depth of about 58 m below ground surface (BGS) with a core barrel, and the drill core was collected (see below). This hole was left open for borehole geophysical logging. Upon our arrival at the borehole it was found to have caved at 18.2 m below the top of the well casing (BTOC; the well casing sticks up about 1 m above ground). Groundwater was cascading into the open hole above the measured static water level of 15.7 m BTOC. Because the cave-in presented a high risk of potential tool loss and there was only about 3 m of water standing in the hole, only two logs were acquired: three-arm caliper and Optical Borehole Image logs.

Logging involves setting up a winch and pulley assembly at the borehole head. The winch controls a single conductor, stainless steel cable on which the slim-hole tools are attached at one end and a data logger attached at the other end. Each tool is “zeroed” at the top of the casing for depth referencing from the Earths surface using a Mount Sopris 5MXA-1000 Matrix Portable Digital Logging System connected to a laptop computer. These tools allow for real time data acquisition and inspection. Tools are deployed down- or up-hole depending on the type of log to be acquired. The Mount Sopris Instruments 2PCA-1000 three-arm caliper tool with 0.5 mm accuracy was run first from the bottom of the hole upwards, beginning just above the cave-in. Once the tool was lowered to the desired depth the arms were opened and the tool was raised up through the hole at a rate of about 3 m per minute. The resulting measurements are the average diameter of the borehole versus depth. The Advanced Logic Technology Optical Borehole Imager (OBI) 40 is a sophisticated downhole camera that generates a static, continuous, 360° image of the borehole walls that is oriented to magnetic or true north by using an internal magnetometer. The camera has an internal light source and is capable of 0.5 mm vertical resolution and 720 pixel azimuthal resolution.

When plotted using a computer program such as WellCAD, the cylindrical log is essentially "unwrapped" onto a flat plane resulting in an image composed of picture elements (pixels) that in total make a raster image of the borehole wall versus depth. This type of log is in many ways superior to a drill core for documentation and measurement of the in-situ conditions in the borehole because the log does not suffer from damaging effects of core drilling, recovery, or lack of orientation. In particular, the orientations and intensity (number of features per unit line length) of joints, faults, veins, bedding, and other features such as fracture aperture or bed thickness can be measured directly from the logs. Any planar to curviplanar feature that intersects the hole can be measured and its depth or depth interval can be recorded. For example, a horizontal joint intersecting the borehole will show up in the log as a single horizontal line, whereas dipping joints form sinusoids. The peak and trough of the sinusoid directly gives the dip inclination from horizontal as well as the dip direction from which the strike is 90° away. These data can be rapidly determined and recorded in a spreadsheet, and because the downhole position is also recorded a new log of joint intensity (number of features per unit line length) can be generated.

Drill Core Logging

Drill core from hole B8 was logged in the field by Shannon and Wilson, Inc. (2008), by using standard methods for identifying rock type, rock quality designations, and percent recovery. The core was boxed in vertical succession and transported to the U.S. Geological Survey where it is currently stored (library record number V099, EPA B8 Standard 13S-87W-36). The drill core was logged for more detailed lithology, mineralogy, hydrothermal alteration and structural characterization, and sampling (table 2). Mineral identification was done using standard methods.

Estimates of Intergranular Porosity and Permeability by MICP

In order to begin understanding the hydraulic properties of the rocks in Elk Basin and the roles of intergranular pore space versus macroscopic fracture networks in the storage and transmission of groundwater and solutes, a small set of samples was submitted for MICP measurements. The analyses, completed by PetroTech Associates in Houston, Texas, are a hydrocarbon industry standard for estimating the intergranular porosity and permeability of the samples (for example, Swanson, 1981). It must be understood that the permeability values measured in this analysis are intergranular (or rock matrix) values and do not represent the permeability related to macroscopic joints or fractures in the rock. The bulk permeability of joint networks is likely much higher than the permeability of the matrix and probably better approximates on a site scale the bulk or overall average permeability of the Ohio Creek Member and Wasatch Formation. The intergranular permeability measurements presented here can thus be viewed as a minimum estimate of the bulk permeability for these formations.

Surface outcrop samples of the Ohio Creek and Wasatch and a subsurface sample of clay-rich gouge from the Standard fault vein, approximately 1 cm^3 in size, were placed in a pressure cell and flooded with mercury while the pressure in the cell was monitored. Entry pressure and bulk intrusion volume versus time were monitored and recorded during the flooding. The plots of these data show distinct peaks and plateaus where peak pressures correspond with grain-scale pore throats that are sufficiently flooded to allow mercury to flow through; these pressures reflect the minimum permeability of the sample. Empirical relationships developed by Swanson (1981) were used to estimate the intrinsic, intergranular, equivalent liquid permeability of each sample. Thus, peak pressures for each sample were chosen and the corresponding permeability was computed. Hydraulic conductivity can also be estimated from the permeability values and assumed but reasonable values of fluid density and viscosity. Porosity is calculated directly from the maximum volume of mercury intruded compared with the total volume of the sample corrected for density of the rock medium and the fluid (table 3).

55-Element ICP–AES–MS Rock Geochemistry

Twenty-two rock samples were collected from outcrops for geochemical analysis, three of which are clay-rich gouge collected from the Level 3 and Level 5 tunnels of the Standard Mine (table 4). Whole-rock samples were returned to the lab and washed in deionized water, and a representative portion was split, ground using an agate ball-mill, and sieved to 200 mesh. Each sample was tested for its concentration of 55 major (except silicon and sodium (Si and Na) rare Earth and trace elements by using inductively coupled plasma-atomic emission spectrometry (ICP–AES) and by inductively coupled plasma-mass spectrometry (ICP–MS). Each 0.1 g sample is decomposed by using a sodium peroxide sinter at 450°C. The resultant cake is leached with water and acidified with nitric acid. After an addition of tartaric acid, aliquots of the digested sample are aspirated into the ICP–AES and the ICP–MS and the concentrations of the optimal elements from the ICP–AES and ICP–MS are determined. The ICP–AES is calibrated with standardized digested-rock reference materials and a series of multi-element solution standards. The ICP–MS is calibrated with aqueous standards, and internal standards are used to compensate for matrix effects and internal drifts. To monitor the quality of the data, a quality control reference

Table 2. Drill Core Log from Borehole B8, Standard Mine, Elk Basin, Colorado.

[Core logged by Barney Berger and Andrew Manning at USGS Core Library, Lakewood, CO, Boxes 1-12 logged 6/26/09, boxes 13-21 logged 7/2/09, Definitions: SA = same as, SAA = same as above (overlying interval), S&W = Shannon and Wilson, Inc. (produced initial core log), steeply dipping = dipping >45 degrees, oxidized fracture = fracture with iron oxide(s) coating fracture surface, WSP = weak quartz-sericite-pyrite alteration, Highly, moderately, and weakly fractured = see attached photographs for examples, Veinlets = veins <1mm wide. Without voids unless otherwise noted, py = pyrite, qtz = quartz, sphal = sphalerite]

Box No.	Top Depth (ft)	Bottom Depth (ft)	Lithology	Structure	Alteration	Mineralogy
1	0.0	6.0	SA log by S&W	Highly fractured, fracture dips variable, mostly oxidized.	Pervasively altered, WSP with oxidation halos 1–2 cm wide focused along fractures	Disseminated py (<1%). Steeply dipping veinlets contain qtz and py.
1	6.0	9.5	SAA	Weakly to moderately fractured, fractures steeply dipping or sub-horizontal, mostly oxidized.	SAA	SAA
2	9.5	18.4	SAA	Weakly fractured, fractures steeply dipping (oxidized) or subhorizontal (variably oxidized).	Pervasively altered, WSP, some organics-rich layers.	Disseminated py (<1%). Veinlets SAA but contain some voids. Steeply dipping vein at 18 ft 2–5 mm wide and contains mainly qtz and py, but py largely weathered away.
3	18.4	20	SAA	Highly fractured, fracture dips variable, mostly oxidized.	SAA	Disseminated py (<1%). Veinlets SAA but contain some carbonate.
3	20	27.7	SA log by S&W, but contact between sandstone and interbedded conglomerate/sandstone at 22.0 ft, not 25.8 ft.	Weakly fractured, fractures steeply dipping (mostly oxidized) or subhorizontal (mostly unoxidized).	SAA	SAA
4	27.7	38.4	SA log by S&W, but contact between interbedded conglomerate/sandstone and sandstone at 37.0 ft, not 34.2 ft.	Weakly fractured, fractures subhorizontal, mostly unoxidized.	SAA	Disseminated py (<1%). Few steeply dipping veinlets, contain qtz, py, and carbonate.
5	38.4	45.8	SA log by S&W, but sandstone 37–42 ft is dark grey and organics-rich.	Weakly fractured, fractures subhorizontal and steeply dipping, nearly all oxidized.	SAA	Disseminated py, generally <1%, but 1–10% in organics-rich interval. Many variably oriented veinlets contain SAA.
6	48.5	55	SA log by S&W	SAA, except highly fractured and fracture dips variable 54.5–55 ft.	SAA	Disseminated py, generally <1%, but locally higher in occasional clots. Veinlets contain qtz, py, and sphal (py dominant in some).

Table 2. Drill Core Log from Borehole B8, Standard Mine, Elk Basin, Colorado.—Cont.

[Core logged by Barney Berger and Andrew Manning at USGS Core Library, Lakewood, CO, Boxes 1-12 logged 6/26/09, boxes 13-21 logged 7/2/09, Definitions: SA = same as, SAA = same as above (overlying interval), S&W = Shannon and Wilson, Inc. (produced initial core log), steeply dipping = dipping >45 degrees, oxidized fracture = fracture with iron oxide(s) coating fracture surface, WSP = weak quartz-sericite-pyrite alteration, Highly, moderately, and weakly fractured = see attached photographs for examples, Veinlets = veins <1mm wide. Without voids unless otherwise noted, py = pyrite, qtz = quartz, sphal = sphalerite]

Box No.	Top Depth (ft)	Bottom Depth (ft)	Lithology	Structure	Alteration	Mineralogy
7	55	63	SAA	Moderately to highly fractured, fracture orientation variable, nearly all oxidized, clay-rich gouge at 63 ft.	Pervasively altered, WSP.	Disseminated py (<1%). Veinlets (mostly steeply dipping) contain mostly py with qtz, carbonate, galena, and sphal.
7	63	64.5	SAA	Weakly fractured, fracture orientation subhorizontal or steeply dipping, unoxidized.	SAA	SAA, but vein at 63.2 ft 1–5 mm wide and contains qtz, py, chalcopyrite, galena, sphal,sericite, and carbonate.
8	64.5	73.2	SA log by S&W, but argillite/siltstone unit is actually sandstone/siltstone, dark grey and organics-rich. Also, bottom of this unit at 74 ft, not 73.2 ft.	Weakly fractured, fracture orientation steeply dipping, mostly unoxidized.	SAA	Disseminated py (<1%). Mostly steeply dipping veinlets contain qtz, py, chalcopyrite, galena, sphal,sericite, and carbonate. Steeply dipping veins at 65.0 ft (1 cm wide), 66.2 feet (1–5 mm wide, with voids), and 71.5 ft (1–5 mm wide, with voids) contain same minerals as veinlets.
9	73.2	82.2	SA log by S&W	Weakly fractured, fracture dips variable, steeply dipping oxidized and subhorizontal unoxidized.	SAA	Disseminated py (<1%). Mostly steeply dipping veinlets contain same minerals as veinlets above, but less carbonate. Steeply dipping vein at 75.0 ft and multiple steeply dipping and subhorizontal veins at 81.0–82.2 ft contain same minerals as veinlets, but also some massive clots of sphal (widths up to 2 cm) and many voids.

Table 2. Drill Core Log from Borehole B8, Standard Mine, Elk Basin, Colorado.—Cont.

[Core logged by Barney Berger and Andrew Manning at USGS Core Library, Lakewood, CO, Boxes 1-12 logged 6/26/09, boxes 13-21 logged 7/2/09, Definitions: SA = same as, SAA = same as above (overlying interval), S&W = Shannon and Wilson, Inc. (produced initial core log), steeply dipping = dipping >45 degrees, oxidized fracture = fracture with iron oxide(s) coating fracture surface, WSP = weak quartz-sericite-pyrite alteration, Highly, moderately, and weakly fractured = see attached photographs for examples, Veinlets = veins <1mm wide. Without voids unless otherwise noted, py = pyrite, qtz = quartz, sphal = sphalerite]

Box No.	Top Depth (ft)	Bottom Depth (ft)	Lithology	Structure	Alteration	Mineralogy
10	82.2	91	SAA	Weakly fractured, fracture orientation subhorizontal and steeply dipping, variably oxidized.	SAA	Disseminated py (<1%). Mostly steeply dipping veinlets (some with voids and oxidation) contain same minerals as veinlets above. Shallow dipping vein at 85.0 ft 1 cm wide and contains same minerals as veinlets.
11	91	99.7	SA log by S&W, but argillite/siltstone unit is actually sandstone/siltstone, dark grey and organics-rich.	Weakly fractured, fracture dips variable, some oxidation.	SAA	Disseminated py (<1%). Mostly steeply dipping veinlets (some with voids and oxidation) contain same minerals as veinlets above, but more galena. Subhorizontal veins at 92.4 ft, 95.7 ft, and 99.2 ft are 0.5–2 cm wide and contain mainly py and sphal, with qtz, chalcopyrite, galena, and sericite.
12	99.7	108.4	SA log by S&W, but argillite/siltstone unit is actually sandstone/siltstone, dark grey and organics-rich.	Moderately fractured, mainly along veins, fracture orientation mainly steeply dipping, unoxidized.	SAA	Disseminated py generally <1%, but 1–10% in organic-rich layers. More intense veining. Veinlets SAA, but less voids and oxidation. Steeply dipping veins at 102.5–106.0 ft are 2–10 cm wide (some voids) and contain mainly py, sphal, and galena, with qtz, chalcopyrite, and sericite

Table 2. Drill Core Log from Borehole B8, Standard Mine, Elk Basin, Colorado.—Cont.

[Core logged by Barney Berger and Andrew Manning at USGS Core Library, Lakewood, CO, Boxes 1-12 logged 6/26/09, boxes 13-21 logged 7/2/09, Definitions: SA = same as, SAA = same as above (overlying interval), S&W = Shannon and Wilson, Inc. (produced initial core log), steeply dipping = dipping >45 degrees, oxidized fracture = fracture with iron oxide(s) coating fracture surface, WSP = weak quartz-sericite-pyrite alteration, Highly, moderately, and weakly fractured = see attached photographs for examples, Veinlets = veins <1mm wide. Without voids unless otherwise noted, py = pyrite, qtz = quartz, sphal = sphalerite]

Box No.	Top Depth (ft)	Bottom Depth (ft)	Lithology	Structure	Alteration	Mineralogy
13	108.4	116.9	SA log by S&W	Weakly fractured, fracture dips variable, mostly oxidized. Highly fractured and fracture orientation variable at 108.4–108.6 ft.	SAA	Disseminated py (<1%). Mostly steeply dipping veinlets (with voids) contain qtz, py, chalcopyrite, galena, sphal, and sericite. Steeply dipping veins at 112.5–114.5 ft are 1–5 cm wide and contain mainly py, sphal, galena, and qtz; large voids up to 1 cm wide, crystals large and generally unoxidized. Steeply dipping veins at 115.0–116.0 ft are 2 mm–1 cm wide and contain same minerals as veinlets (some oxidation). Major subvertical void at 109.0–109.5 (oxidized).
14	116.9	125.8	SAA	Weakly fractured, fracture orientation mainly steeply dipping, some oxidation. 122.3–122.5 ft highly fractured, fracture dips variable, and highly oxidized.	SAA	Disseminated py (<1%). Mostly steeply dipping veinlets (few voids, little oxidation) contain same minerals as veinlets above. Veins at 117.0 ft (subhorizontal), 120.5 ft (steeply dipping), and 122.5–123.0 ft (steeply dipping) all 1–2 cm wide and contain same minerals as veins above (some voids, weakly oxidized).

Table 2. Drill Core Log from Borehole B8, Standard Mine, Elk Basin, Colorado.—Cont.

[Core logged by Barney Berger and Andrew Manning at USGS Core Library, Lakewood, CO, Boxes 1-12 logged 6/26/09, boxes 13-21 logged 7/2/09, Definitions: SA = same as, SAA = same as above (overlying interval), S&W = Shannon and Wilson, Inc. (produced initial core log), steeply dipping = dipping >45 degrees, oxidized fracture = fracture with iron oxide(s) coating fracture surface, WSP = weak quartz-sericite-pyrite alteration, Highly, moderately, and weakly fractured = see attached photographs for examples, Veinlets = veins <1mm wide. Without voids unless otherwise noted, py = pyrite, qtz = quartz, sphal = sphalerite]

Box No.	Top Depth (ft)	Bottom Depth (ft)	Lithology	Structure	Alteration	Mineralogy
15	125.8	134.6	SAA	Generally weakly fractured, fracture orientation mainly steeply dipping, mostly oxidized. 128.0–129.0 ft and 131.9–132.1 ft highly fractured with gouge and possible fault in each interval.	SAA	Disseminated py 1–10%, py largely oxidized (unlike above), core has yellowish color apparently due to pervasive oxidation. Mostly steeply dipping veinlets contain same minerals as veinlets above (some voids, some oxidation). Steeply dipping veins at 126.0–126.5 ft, 128.0 ft, 130.0–130.5 ft, and 131.0 ft are 2 mm–1 cm wide and contain same minerals as veins above (minor voids, minor oxidation).
16	134.6	143.2	SAA	Weakly fractured, fracture dips variable, some oxidation. 136.1 ft gouge and possible small fault.	SAA	Disseminated py 1–10%. Mostly steeply dipping veinlets contain same minerals as veinlets above (voids, some oxidation).
17	143.2	149.5	SAA	Weakly fractured, fracture dips variable, some oxidation. Clay-rich seam at 145.0 ft, could be drilling mud or fault gouge.	SAA	Disseminated py 1–10%. Veinlets SAA. Steeply dipping vein at 149.0 ft is 5 cm wide and contains same minerals as veins above (voids and some oxidation).
17	149.5	152	SAA	Highly fractured, fracture dips variable, highly oxidized.	SAA	Disseminated py 1–10%. Veinlets SAA. Steeply dipping vein at 151.8 ft is 2–4 cm wide and contains same minerals as veins above (voids and highly oxidized).
18	152	154	SAA	SAA	SAA	Disseminated py 1–2%. Veinlets SAA.
18	154	158	SAA	Weakly fractured, fracture orientation mostly steeply dipping, mostly oxidized.	SAA	SAA

Table 2. Drill Core Log from Borehole B8, Standard Mine, Elk Basin, Colorado.—Cont.

[Core logged by Barney Berger and Andrew Manning at USGS Core Library, Lakewood, CO, Boxes 1-12 logged 6/26/09, boxes 13-21 logged 7/2/09, Definitions: SA = same as, SAA = same as above (overlying interval), S&W = Shannon and Wilson, Inc. (produced initial core log), steeply dipping = dipping >45 degrees, oxidized fracture = fracture with iron oxide(s) coating fracture surface, WSP = weak quartz-sericite-pyrite alteration, Highly, moderately, and weakly fractured = see attached photographs for examples, Veinlets = veins <1mm wide. Without voids unless otherwise noted, py = pyrite, qtz = quartz, sphal = sphalerite]

Box No.	Top Depth (ft)	Bottom Depth (ft)	Lithology	Structure	Alteration	Mineralogy
18	158	160	SAA	Highly fractured, fracture dips variable, mostly oxidized. Possible gouge at 159.0 ft.	SAA	SAA
18	160	161.6	SAA	Weakly fractured, fracture orientation steeply dipping, oxidized.	SAA	SAA
19	161.6	170	SA log by S&W, but 167–168 mudstone/shale, not sandstone.	Weakly fractured, fracture orientation steeply dipping, some oxidation.	SAA	Disseminated py 1–2%. Veinlets SAA. Steeply dipping vein at 170.0 ft is 1–2 cm wide and contains mostly qtz (well-formed crystals), open and highly oxidized
20	170	178.8	Breccia 173.0–178.8 ft, sedimentary structure highly chaotic, no apparent bedding, variable grain size.	SAA. Possible gouge at 172.5 feet in steeply dipping fracture, oxidized.	SAA	Disseminated py 1–2% in sandstone, 1–10% in breccia. Veinlets SAA. Steeply dipping vein at 175.0 ft is 2 cm wide and contains qtz, py, chalcopyrite, galena, sphal, and sericite, but has qtz/carbonate core (highly oxidized).
21	178.8	181	SA log by S&W, but breccia 178.8–179.5 ft, and a lot of carbonate in matrix 185.0–187.5 ft.	Weakly fractured, fracture dips variable, some oxidation.	SAA	Disseminated py 1–2%. Veinlets SAA. Steeply dipping veins at 179.5 ft and 181.0 ft are 1–2 cm wide and contains same minerals as veins above.
21	181	187.5	SA log by S&W, but a lot of carbonate in matrix 185.0–187.5 ft.	Highly fractured, fracture dips variable, low oxidation.	SAA	Disseminated py 1–2%. Veinlets SAA. Extensive variably oriented veins at 185.0–187.5 ft are up to 5 cm wide and contain mainly qtz with minor py and sphal.

Table 3. Elk Basin mercury injection capillary pressure rock sample porosity and permeability data.

[Abbreviations: Kmvo = Upper Cretaceous Ohio Creek Member, Tw = Tertiary Wasatch Formation, CRG = Clay-Rich Gouge from Standard fault-vein level 3, $k_{clean\ sand}$ = permeability estimated from Swanson (1981) equation for clean sand, m = meters, K = hydraulic conductivity, s = seconds, STP = Standard Pressure Temperature]

Sample number	Lithology	Porosity (%)	Median aperture (microns)	Capillary pressure at maximum intrusion (psia)	Aperture at maximum pore volume intrusion (microns)	Cumulative bulk volume at maximum intrusion (%)	$k_{clean\ sand}$ (m^2)	K (m/s, STP)	Pore structure
70909 14A	Kmvo	9.2	0.551	209	1.021	3.67	8.5E-17	8.4E-10	weak bimodal
72109 4A	CRG	21.3	0.055	3,100	0.069	12.06	3.6E-18	3.5E-11	unimodal
72209 10A	Tw	0.7	0.016	20,400	0.011	0.69	1.6E-22	1.6E-15	unimodal

Table 4. Elemental geochemistry of fault vein related rock samples from Elk Basin and the Standard Mine, Colorado.

[USGS National Geochemical Databse job number MRP-10035, 22 Samples, 55 Element ICPAES-MS. Abbreviations: USGS = U.S. Geological Survey, MRP = mineral resources program, ICPAES-MS = inductively coupled plasma-atomic emission and mass spectrometry, No. = Number, Ft = feet, std = standard, oc = outcrop, L1 = level 1 (3 and 5), fv = fault vein, m = meter, se = southeast, nw = northwest, flt = fault, B8 = borehole 8, WGS84 = world geodetic survey 1984 (all GPS data uses this coordiante system), dd= decimal degrees, Z = elavation above dataum, PDOP = positional (3D) dilution of precision, Arch = arcitecture, hw = hanging wall, pl = protolith, fw = footwall, dz = damage zone, qtz = quartz, sst = sandstone, min= mineralized, arg = argillized, ox = oxidized, Kmvo = Upper Cretaceous Ohio Creek, cata = cataclasite, CRG = clay-rich gouge, py = pyrite, unox = unoxidized, polymet = polymetallic, Tw = Tertiary Wasatch, Tqmp = Tertiary quartz monzonite porphry, % = percent, ppm = parts per million]

USGS Lab No.	Sample No.	Location	LON (dd)	LAT (dd)	Z (m)	PDOP	Fault Arch	Simple Lithology	Unit
C-327497	70909 5A	std mine oc	–107.0758	38.8787	3,340.1	7.8	core	qtz vein	vein
C-327498	70909 6A	std mine oc	–107.0758	38.8786	3,260.0	2.9	hwpl	qtz sst	Tw
C-327499	70909 7A	std mine oc	–107.0751	38.8794	3,349.4	2.9	fwpl	qtz sst	Kmvo
C-327500	70909 8A	std mine L1, fv, ~1m se of core	–107.0737	38.8801	3,367.6	1.8	hwdz	min qtz sst	Tw
C-327501	70909 8B	std mine L1, fv, ~4m se of core	–107.0737	38.8800	3,367.6	1.8	hwpl	ox qtz sst	Tw
C-327502	70909 8C	std mine L1, fv, ~1m nw of core	–107.0738	38.8801	3,367.6	1.8	fwdz	ox qtz sst	Kmvo
C-327503	70909 14A	std mine L3, fv, ~100m nw of flt	–107.0706	38.8831	3,440.6	2.7	fwpl	qtz sst	Kmvo
C-327504	70909 14B	std mine L3, fv, ~2m nw of flt	–107.0702	38.8824	3,440.6	2.7	fwdz	qtz sst	Kmvo
C-327505	70909 14C	std mine L3, fv, ~2m se of flt	–107.0701	38.8823	3,440.6	2.7	hwdz	qtz sst	Tw
C-327506	70909 14D	std mine L3, fv, ~20m se of flt	–107.0700	38.8822	3,440.6	2.7	hwpl	qtz sst	Tw
C-327507	72009 1A	std mine oc	–107.0765	38.8783	3,356.6	2.4	fwpl	porphry	Tqmp
C-327508	72109 3A	std mine L3, fv, 7m n of MSTD34	–107.0697	38.8826	3,440.6	na	core	Kmvo cata	crg
C-327509	72109 4A	std mine L3, fv, ecmstdl35, n end tunnel	–107.0696	38.8826	3,440.6	na	core	crg	crg
C-327510	72209 1A	std mine L5, fv, 168ft ne of portal	–107.0677	38.8834	3,360.8	na	core	py crg	crg
C-327511	72209 1B	std mine L5, fv, 168ft ne of portal, ~1m from core	–107.0677	38.8834	3,360.8	na	fwdz	qtz sst	Kmvo
C-327512	72209 1C	std mine L5, fv, 197ft ne of portal, ~1m from core	–107.0676	38.8834	3,360.8	na	hwdz	qtz sst	Tw
C-327513	72209 10A	elk basin oc	–107.0678	38.8825	3,526.5	na	hwpl	unox qtz sst	Tw
C-327514	72209 11A	elk basin oc	–107.0670	38.8856	3,559.5	na	fwpl	ox qtz sst	Kmvo
C-327515	72209 14A	elk basin oc	–107.0705	38.8805	3,405.3	na	hwpl	unox porphyry	Tqmp
C-327516	72409 43A	elk fault oc sw tip	–107.0779	38.8799	3,435.5	na	hwdz	arg Tw	Tw veins
C-327517	B8 75 ft	std drill core B8	–107.0717	38.8814	3,415.5	0.1 (m)	fwdz	qtz sst	Kmvo
C-327518	B8 113 ft	std drill core B8	–107.0717	38.8814	3,415.5	0.1 (m)	fwdz	polymet vein	Kmvo

Table 4. Elemental geochemistry of fault vein related rock samples from Elk Basin and the Standard Mine, Colorado.—Cont.

[USGS National Geochemical Databse job number MRP-10035, 22 Samples, 55 Element ICPAES-MS. Abbreviations: USGS = U.S. Geological Survey, MRP = mineral resources program, ICPAES-MS = inductively coupled plasma-atomic emission and mass spectrometry, , No. = Number, Ft = feet, std = standard, oc = outcrop, L1 = level 1 (3 and 5), fv = fault vein, m = meter, se = southeast, nw = northwest, flt = fault, B8 = borehole 8, WGS84 = world geodetic survey 1984 (all GPS data uses this coordiante system), dd= decimal degrees, Z = elevation above dataum, PDOP = positional (3D) dilution of precision, Arch = arcitecture, hw = hanging wall, pl = protolith, fw = footwall, dz = damage zone, qtz = quartz, sst = sandstone, min= mineralized, arg = argillized, ox = oxidized, Kmvo = Upper Cretaceous Ohio Creek, cata = cataclasite, CRG = clay-rich gouge, py = pyrite, unox = unoxidized, polymet = polymetallic, Tw = Tertiary Wasatch, Tqmp = Tertiary quartz monzonite porphry, % = percent, ppm = parts per million]

Sample No.	Al %	Ca %	Fe %	K %	Mg %	Mn %	P %	Ti %	Ag ppm	As ppm	Ba ppm	Be ppm	Bi ppm	Cd ppm	Ce ppm	Co ppm
70909 5A	2.16	0.07	0.67	1.05	0.12	0.02	<0.01	0.11	<1	300	192	<5	0.1	<0.2	17.9	<0.5
70909 6A	7.81	2.21	2.25	1.65	0.48	0.09	0.08	0.21	<1	<30	1,420	<5	<0.1	<0.2	64.1	5
70909 7A	5.43	0.95	0.83	1.89	0.18	0.04	0.03	0.16	<1	<30	406	<5	<0.1	<0.2	66.9	8.6
70909 8A	0.35	0.07	8.1	0.14	0.01	0.01	<0.01	<0.01	51	490	56.8	<5	1	9.2	2.8	4
70909 8B	5.34	0.2	1.56	1.87	0.16	0.19	0.03	0.26	<1	<30	371	<5	<0.1	1.6	72.5	7.6
70909 8C	5.8	0.2	0.42	2.73	0.24	0.04	0.04	0.21	<1	<30	653	<5	<0.1	0.3	76.7	0.6
70909 14A	4.86	0.07	0.73	3.24	0.17	0.08	0.02	0.07	<1	<30	675	<5	<0.1	0.4	47.5	2.9
70909 14B	2.86	0.08	1.37	1.28	0.1	0.03	0.01	0.06	1	40	409	<5	0.1	<0.2	48.9	0.6
70909 14C	7.95	1.4	3.24	2.86	1.1	0.24	0.02	0.28	<1	<30	820	<5	0.1	2.8	101	8.1
70909 14D	9.48	3.01	2.6	1.45	0.44	0.08	0.1	0.31	<1	<30	1,010	<5	<0.1	0.8	73.2	8.9
72009 1A	7.23	0.4	2.36	3.18	0.71	0.18	0.09	0.24	<1	<30	1,070	<5	<0.1	<0.2	84.7	6.5
72109 3A	9.54	0.22	1	3.87	0.27	0.07	0.06	0.48	<1	30	968	6	0.4	2.6	149	5.6
72109 4A	10.7	0.41	3.94	4.92	0.35	0.72	0.02	0.48	3	60	1,190	7	0.3	23.2	215	5.1
72209 1A	8.9	0.14	2.12	4.06	0.31	0.34	<0.01	0.32	2	50	1,500	<5	0.2	7.7	87.8	3.7
72209 1B	4.4	0.05	0.9	2.29	0.16	0.04	0.01	0.15	<1	50	609	<5	<0.1	0.9	67.7	4.2
72209 1C	7.41	1.51	3.28	2.99	0.67	0.35	0.02	0.28	<1	<30	814	<5	0.1	0.3	104	9.8
72209 10A	8.43	2.75	5.54	1.2	0.79	0.16	0.14	0.59	<1	<30	391	<5	<0.1	<0.2	81.1	13.8
72209 11A	5.03	1.49	0.89	2.33	0.21	0.11	0.02	0.11	<1	30	737	<5	<0.1	0.5	62	7
72209 14A	7.55	1.21	2.35	3.27	0.65	0.16	0.08	0.24	<1	<30	1,380	<5	0.2	0.3	84.1	6.8
72409 43A	5.8	0.22	1.17	2.81	0.25	0.03	0.01	0.27	1	330	405	<5	<0.1	<0.2	63.5	<0.5
B8 75 ft	3.34	0.24	2.88	1.46	0.19	0.27	0.02	0.15	4	70	330	<5	<0.1	17.8	51.3	5.9
B8 113 ft	0.01	0.04	27.6	0.04	<0.01	0.16	<0.01	<0.01	138	1,860	10	<5	10.9	390	0.4	26.3

Table 4. Elemental geochemistry of fault vein related rock samples from Elk Basin and the Standard Mine, Colorado.—Cont.

[USGS National Geochemical Databse job number MRP-10035, 22 Samples, 55 Element ICPAES-MS. Abbreviations: USGS = U.S. Geological Survey, MRP = mineral resources program, ICPAES-MS = inductively coupled plasma-atomic emission and mass spectrometry, No. = Number, Ft = feet, std = standard, oc = outcrop, L1 = level 1 (3 and 5), fv = fault vein, m = meter, se = southeast, nw = northwest, flt = fault, B8 = borehole 8, WGS84 = world geodetic survey 1984 (all GPS data uses this coordiante system), dd= decimal degrees, Z = elavation above dataum, PDOP = positional (3D) dilution of precision, Arch = arcitecture, hw = hanging wall, pl = protolith, fw = footwall, dz = damage zone, qtz = quartz, sst = sandstone, min= mineralized, arg = argillized, ox = oxidized, Kmvo = Upper Cretaceous Ohio Creek, cata = cataclasite, CRG = clay-rich gouge, py = pyrite, unox = unoxidized, polymet = polymetallic, Tw = Tertiary Wasatch, Tqmp = Tertiary quartz monzonite porphry, % = percent, ppm = parts per million]

Sample No.	Cr ppm	Cs ppm	Cu ppm	Dy ppm	Er ppm	Eu ppm	Ga ppm	Gd ppm	Ge ppm	Hf ppm	Ho ppm	In ppm	La ppm	Li ppm	Lu ppm	Mo ppm
70909 5A	10	1.8	8	0.77	0.47	0.2	6	0.85	<1	2	0.18	<0.2	8.9	30	0.09	<2
70909 6A	<10	5.2	7	3.72	2.01	1.72	18	4.79	2	4	0.71	<0.2	33.4	20	0.32	<2
70909 7A	20	3.5	8	2.89	1.73	0.9	12	3.33	1	5	0.6	<0.2	33.3	10	0.25	<2
70909 8A	<10	0.2	351	0.13	0.1	<0.05	<1	0.12	<1	<1	<0.05	0.4	1.5	30	<0.05	<2
70909 8B	20	3.4	7	3.88	2.39	0.92	12	3.72	1	10	0.79	<0.2	30.9	40	0.41	<2
70909 8C	20	4	18	3.74	2.27	1.1	14	4.49	1	5	0.81	<0.2	40.6	50	0.36	<2
70909 14A	10	2.5	<5	1.9	1.04	0.61	10	2.42	1	3	0.37	<0.2	24.3	20	0.17	<2
70909 14B	10	1.6	23	1.88	0.99	0.48	7	2.47	1	2	0.36	<0.2	25.3	30	0.16	<2
70909 14C	10	7.7	12	4.95	2.52	2.95	19	7.18	1	6	0.99	<0.2	68	30	0.37	<2
70909 14D	<10	8.3	<5	3.82	2.13	2.11	21	5.17	1	4	0.8	<0.2	37.5	40	0.31	<2
72009 1A	10	2	<5	3.81	2.11	1.4	18	4.8	<1	5	0.73	<0.2	44.8	20	0.31	<2
72109 3A	60	14.6	2,140	7.84	4.66	2.77	25	8.08	<1	7	1.63	1.2	67.4	120	0.69	<2
72109 4A	30	45.6	448	9.42	5.09	2.82	30	11.1	1	6	1.91	<0.2	94	10	0.7	3
72209 1A	20	14.1	24	5.31	3.17	1.61	22	5.27	<1	5	1.13	<0.2	43.6	50	0.5	6
72209 1B	<10	3.4	64	2.39	1.48	0.74	11	3.13	1	5	0.5	<0.2	35.3	10	0.19	<2
72209 1C	<10	10.9	8	4.48	2.21	2.27	18	6.37	1	7	0.82	<0.2	52.8	20	0.36	<2
72209 10A	10	2.7	<5	5.75	3.17	2.54	23	7.08	2	7	1.12	<0.2	40.7	30	0.48	<2
72209 11A	10	4.2	<5	3.85	2.09	1.14	12	4.18	1	4	0.81	<0.2	32.5	<10	0.33	<2
72209 14A	<10	2.1	<5	3.88	2.04	1.64	18	5.02	2	5	0.74	<0.2	42.8	10	0.34	<2
72409 43A	<10	2.4	<5	3	2.04	0.51	18	3.42	1	5	0.67	<0.2	32.4	<10	0.38	<2
B8 75 ft	20	2.8	75	3	1.66	0.72	9	3.26	2	5	0.6	<0.2	27	60	0.26	<2
B8 113 ft	<10	<0.1	>10,000	<0.05	<0.05	<0.05	<1	<0.05	1	<1	<0.05	19.4	0.2	<10	<0.05	<2

Table 4. Elemental geochemistry of fault vein related rock samples from Elk Basin and the Standard Mine, Colorado.—Cont.

[USGS National Geochemical Databse job number MRP-10035, 22 Samples, 55 Element ICPAES-MS. Abbreviations: USGS = U.S. Geological Survey, MRP = mineral resources program, ICPAES-MS = inductively coupled plasma-atomic emission and mass spectrometry, No. = Number, Ft = feet, std = standard, oc = outcrop, L1 = level 1 (3 and 5), fv = fault vein, m = meter, se = southeast, nw = northwest, flt = fault, B8 = borehole 8, WGS84 = world geodetic survey 1984 (all GPS data uses this coordiante system), dd= decimal degrees, Z = elevation above dataum, PDOP = positional (3D) dilution of precision, Arch = arcitecture, hw = hanging wall, pl = protolith, fw = footwall, dz = damage zone, qtz = quartz, sst = sandstone, min= mineralized, arg = argillized, ox = oxidized, Kmvo = Upper Cretaceous Ohio Creek, cata = cataclasite, CRG = clay-rich gouge, py = pyrite, unox = unoxidized, polymet = polymetallic, Tw = Tertiary Wasatch, Tqmp = Tertiary quartz monzonite porphry, % = percent, ppm = parts per million]

Sample No.	Nb ppm	Nd ppm	Ni ppm	Pb ppm	Pr ppm	Rb ppm	Sb ppm	Sc ppm	Sm ppm	Sn ppm	Sr ppm	Ta ppm	Tb ppm	Th ppm	Tl ppm	Tm ppm
70909 5A	4	7.6	<5	288	2	108	2.4	<5	1.3	15	14.8	<0.5	0.13	2.3	2.5	0.09
70909 6A	9	29.8	6	6	7.74	102	0.2	<5	5.6	1	689	<0.5	0.64	4.1	1.8	0.3
70909 7A	8	26.2	15	22	7.47	115	1.4	<5	4.8	2	40.6	<0.5	0.52	8.2	1.9	0.26
70909 8A	<1	0.9	<5	>10,000	0.3	12.3	22.1	<5	0.2	13	13.5	<0.5	<0.05	0.2	<0.5	<0.05
70909 8B	11	25.3	19	281	7.15	124	1	<5	4.7	2	32.7	0.7	0.63	12.2	2.2	0.36
70909 8C	11	32	<5	771	9.01	214	0.6	<5	5.6	5	12.4	0.7	0.66	10.6	5	0.31
70909 14A	5	17.8	<5	380	5.19	210	1.4	<5	2.9	1	34.1	<0.5	0.33	5.9	4	0.15
70909 14B	4	19.8	<5	677	5.66	107	3.4	<5	3.3	8	18.6	<0.5	0.34	4	2	0.14
70909 14C	12	55	7	25	14.4	221	0.3	6	9.5	2	165	0.6	1.01	7.1	4.8	0.33
70909 14D	9	35.8	9	15	9.19	102	0.2	8	6.8	2	1,610	<0.5	0.7	4.5	1.9	0.3
72009 1A	14	37.9	<5	24	10.3	155	0.4	6	6.7	2	237	0.9	0.63	9.4	2.9	0.29
72109 3A	20	59.6	8	2,560	16.9	279	22.9	15	11.3	12	59	1.2	1.26	20.5	4.7	0.69
72109 4A	21	79.2	10	2,360	22	393	4.6	13	15	28	63.6	1.3	1.66	19.1	7.6	0.77
72209 1A	15	34.6	7	587	9.74	413	4.9	8	6.3	34	26.3	0.9	0.89	12.7	8.5	0.48
72209 1B	8	26.8	6	335	7.63	192	3.5	<5	4.7	9	13	<0.5	0.48	9.3	4.7	0.2
72209 1C	12	47.7	5	23	12.7	257	1	6	8.5	2	77	0.6	0.88	7.3	5.5	0.33
72209 10A	12	41.5	5	8	10.3	98.6	0.4	13	8.5	2	711	<0.5	1	4.9	2	0.48
72209 11A	7	26.2	6	29	7.29	132	0.9	<5	5	2	139	<0.5	0.63	7.2	1.9	0.34
72209 14A	12	37.6	6	11	10.1	146	0.2	6	6.4	1	439	0.7	0.71	7.7	3.3	0.32
72409 43A	9	27.5	<5	84	7.56	266	2.5	8	4.4	15	33.4	<0.5	0.48	7.5	5	0.34
B8 75 ft	7	21.3	7	2,880	5.91	103	4.4	<5	3.9	6	20.5	<0.5	0.48	7.4	1.7	0.26
B8 113 ft	<1	0.2	<5	>10,000	<0.05	1.2	82.4	<5	<0.1	65	4.1	<0.5	<0.05	<0.1	<0.5	<0.05

Table 4. Elemental geochemistry of fault vein related rock samples from Elk Basin and the Standard Mine, Colorado.—Cont.

[USGS National Geochemical Databse job number MRP-10035, 22 Samples, 55 Element ICPAES-MS. Abbreviations: USGS = U.S. Geological Survey, MRP = mineral resources program, ICPAES-MS = inductively coupled plasma-atomic emission and mass spectrometry, No. = Number, Ft = feet, std = standard, oc = outcrop, L1 = level 1 (3 and 5), fv = fault vein, m = meter, se = southeast, nw = northwest, flt = fault, B8 = borehole 8, WGS84 = world geodetic survey 1984 (all GPS data uses this coordiante system), dd= decimal degrees, Z = elevation above dataum, PDOP = positional (3D) dilution of precision, Arch = arcitecture, hw = hanging wall, pl = protolith, fw = footwall, dz = damage zone, qtz = quartz, sst = sandstone, min= mineralized, arg = argillized, ox = oxidized, Kmvo = Upper Cretaceous Ohio Creek, cata = cataclasite, CRG = clay-rich gouge, py = pyrite, unox = unoxidized, polymet = polymetallic, Tw = Tertiary Wasatch, Tqmp = Tertiary quartz monzonite porphry, % = percent, ppm = parts per million]

Sample No.	U ppm	V ppm	W ppm	Y ppm	Yb ppm	Zn ppm	Zr ppm
70909 5A	0.74	27	19	4	0.6	12	84.5
70909 6A	0.96	56	<1	18.3	1.8	56	129
70909 7A	1.89	36	1	15.2	1.7	27	167
70909 8A	0.13	6	<1	0.7	<0.1	1630	3.2
70909 8B	2.59	51	2	19.8	2.7	178	365
70909 8C	2.01	38	3	18.8	2.2	69	192
70909 14A	1.44	22	<1	9.2	1.1	113	104
70909 14B	0.94	23	1	8.5	1	101	62.5
70909 14C	1.52	41	<1	26.1	2.3	456	240
70909 14D	0.83	59	<1	19.1	2	185	128
72009 1A	3.21	51	2	18.5	1.9	66	153
72109 3A	6.1	129	5	39.1	4.3	435	254
72109 4A	5.25	132	25	47.4	4.9	1,860	207
72209 1A	3.65	71	3	28.7	3.2	1,040	186
72209 1B	1.89	25	6	11.4	1.4	98	151
72209 1C	1.54	45	2	20.1	2.2	98	261
72209 10A	1.3	126	1	28.8	2.9	101	229
72209 11A	1.36	23	<1	20.4	2	100	127
72209 14A	2.4	51	<1	18.5	2	68	174
72409 43A	1.34	46	24	16.4	2.4	8	173
B8 75 ft	1.52	35	2	14.3	1.6	2,660	172
B8 113 ft	0.08	16	<1	<0.5	<0.1	>10,000	1

standard was included with the samples analyzed. All detectable concentrations of the 55 elements were within 2 standard deviations of the expected mean, except for iron, magnesium, and zinc, which were within 3 standard deviations. All values fell within the acceptance criteria outlined in Arbogast (1990). The analyses were completed at the same time this document was in preparation and thus no further comments are presented here, however the raw data are provided (table 4).

Mineralogy by X-Ray Diffraction

Powder x-ray diffraction (XRD) analyses of whole-rock samples were completed by the U.S. Geological Survey, Boulder, Colorado XRD laboratory (table 5). Approximately 1 g aliquots of each powdered sample prepared for 55-element analyses were also taken for XRD analysis. The powdered sample was mixed with 0.25 g of an internal standard (Al_2O_3, corundum) and ground with 4 ml of methanol in a McCrone micronising mill for 5 min. The mixture was poured into a 50 ml beaker and air dried at 60°C. Each of the dried samples was transferred to a polypropylene scintillation vial and capped with three acrylic balls and 625 µL of Vertrel (a hydroflurocarbon solvent). The vials were clamped in a Spex 8000D mixer/mill and shaken for 10 min., air dried, and shaken again for 10 min. to produce a randomly oriented sample. The powdered sample was sieved through a 500 µm mesh and side loaded into holders. The samples were x-rayed with Cu-K_a radiation from 5º to 65º two theta. After visual inspection of the raw x-ray patterns for major mineral, characteristic peak reflections the computer program RockJock (Eberl, 2003) was used to analyze the x-ray diffraction pattern.

RockJock estimates the weight percent of each mineral by solving the equation:

$$\%_{Mineral}=(I_{min}/MIF)\times(\%_{std}/I_{std}) \text{ (Eberl, 2003),}$$

where $\%_{Mineral}$ is the weight percent of the unknown mineral (50 percent) and the internal standard (25 percent Al_2O_3). I_{min} and I_{std} are the integrated XRD intensities for the unknown mineral and the corundum standard. MIF compares the integrated intensity of the mineral to that of the internal standard (Eberl, 2003). Integrated XRD intensities are determined by whole-pattern fitting (Smith and others, 1987) by using a library of XRD patterns of pure minerals. Several patterns of individual minerals from the library are scaled simultaneously and summed together to create a calculated pattern that is compared to the measured sample pattern. The scaling factors are adjusted automatically until the degree of fit between the measured and calculated patterns is minimized. The error in the analyses is approximately ±3 wt. pct. (1 standard deviation) at 50 wt. pct. of a mineral (Eberl, 2003). Individual mineral concentrations in each sample are normalized to 100 percent and the prenormalization totals are reported. A full-pattern degree of fit parameter is also reported where lower values suggest more accurate analyses, and values less than 0.1 are considered ideal.

Table 5. X-ray diffraction mineralogy for rock samples from Elk Basin, Colorado.

[Abbreviations: USGS = U.S. Geological Survey, MRP = mineral resources program, ICPAES-MS = inductively coupled plasma-atomic emission and mass spectrometry, No. = Number, Ft = feet, std = standard, oc = outcrop, L1 = level 1 (3 and 5), fv = fault vein, m = meter, se = southeast, nw = northwest, flt = fault, B8 = borehole 8, WGS84 = world geodetic survey 1984 (all GPS data uses this coordiante system), dd= decimal degrees, Z = elevation above dataum, PDOP = positional (3D) dilution of precision, Arch = arcitecture, hw = hanging wall, pl = protolith, fw = footwall, dz = damage zone, qtz = quartz, sst = sandstone, min= mineralized, arg = argillized, ox = oxidized, Kmvo = Upper Cretaceous Ohio Creek, cata = cataclasite, CRG = clay-rich gouge, py = pyrite, unox = unoxidized, polymet = polymetallic, Tw = Tertiary Wasatch, Tqmp = Tertiary quartz monzonite porphry, % = percent, ppm = parts per million]

USGS Lab No.	**C-327497**	**C-327498**	**C-327499**	**C-327500**	**C-327501**	**C-327502**
Sample No.	**70909 5A**	**70909 6A**	**70909 7A**	**70909 8A**	**70909 8B**	**70909 8C**
Location	std mine oc	std mine oc	std mine oc	std mine L1, fv, ~1m se of core	std mine L1, fv, ~4m se of core	std mine L1, fv, ~1m nw of core
LON (dd)	–107.076	–107.076	–107.075	–107.074	–107.074	–107.074
LAT (dd)	38.879	38.879	38.879	38.880	38.880	38.880
Z (m)	3,340.1	3,260.0	3,349.4	3,367.6	3,367.6	3,367.6
PDOP	7.8	2.9	2.9	1.8	1.8	1.8
Fault Arch	core	hwpl	fwpl	hwdz	hwpl	fwdz
Simple Lithology	qtz vein	qtz sst	qtz sst	min qtz sst	ox qtz sst	ox qtz sst
Unit	vein	Tw	Kmvo	Tw	Tw	Kmvo
Mineral	**Weight %**	**Weight %**	**Weight %**	**Weight %**	**Weight %**	**Weight %**
NON-CLAYS						
Quartz	87.7	27.8	58.2	73.5	67.2	66.9
Kspar (ordered Microcline)	0.0	0.0	0.4	0.3	0.0	0.0
Kspar (intermediate microcline)	0.2	1.9	0.1	0.8	1.1	0.0
Kspar (sanidine)	0.0	0.0	0.0	0.2	0.0	0.7
Plagioclase (albite, var. cleavelandite)	0.3	14.4	9.7	0.0	0.1	0.1
Plagioclase (oligoclase; Norway)	0.0	20.0	1.7	0.2	0.0	0.0
Plagioclase (anorthite)	0.0	0.9	0.0	0.0	0.0	0.0
Calcite	0.0	4.4	1.6	0.2	0.0	0.0
Amphibole (ferrotschermakite)	0.0	0.0	0.0	0.8	0.0	0.0
Pyrite	0.0	0.0	0.0	17.2	0.1	0.0
Hematite	0.0	0.6	0.0	0.0	0.0	0.0
Goethite	0.0	0.0	0.2	0.0	1.1	0.0
Fluorapatite	0.0	0.5	0.3	0.2	0.0	0.0
Galena	0.0	0.0	0.0	0.5	0.0	0.0
Jarosite (Mex)	1.4	0.5	0.0	0.0	0.0	0.1
Sphalerite	0.0	0.1	0.0	0.7	0.0	0.0
Anglesite	0.0	0.0	0.1	5.5	0.0	0.0
Total non-clays	89.6	71.1	72.2	100.0	69.6	67.9

Table 5. X-ray diffraction mineralogy for rock samples from Elk Basin, Colorado.—Cont.

[Abbreviations: USGS = U.S. Geological Survey, MRP = mineral resources program, ICPAES-MS = inductively coupled plasma-atomic emission and mass spectrometry, No. = Number, Ft = feet, std = standard, oc = outcrop, L1 = level 1 (3 and 5), fv = fault vein, m = meter, se = southeast, nw = northwest, flt = fault, B8 = borehole 8, WGS84 = world geodetic survey 1984 (all GPS data uses this coordiante system), dd= decimal degrees, Z = elavation above dataum, PDOP = positional (3D) dilution of precision, Arch = arcitecture, hw = hanging wall, pl = protolith, fw = footwall, dz = damage zone, qtz = quartz, sst = sandstone, min= mineralized, arg = argillized, ox = oxidized, Kmvo = Upper Cretaceous Ohio Creek, cata = cataclasite, CRG = clay-rich gouge, py = pyrite, unox = unoxidized, polymet = polymetallic, Tw = Tertiary Wasatch, Tqmp = Tertiary quartz monzonite porphry, % = percent, ppm = parts per million]

USGS Lab No.	**C-327497**	**C-327498**	**C-327499**	**C-327500**	**C-327501**	**C-327502**
Sample No.	**70909 5A**	**70909 6A**	**70909 7A**	**70909 8A**	**70909 8B**	**70909 8C**
Location	std mine oc	std mine oc	std mine oc	std mine L1, fv, ~1m se of core	std mine L1, fv, ~4m se of core	std mine L1, fv, ~1m nw of core
LON (dd)	–107.076	–107.076	–107.075	–107.074	–107.074	–107.074
LAT (dd)	38.879	38.879	38.879	38.880	38.880	38.880
Z (m)	3,340.1	3,260.0	3,349.4	3,367.6	3,367.6	3,367.6
PDOP	7.8	2.9	2.9	1.8	1.8	1.8
Fault Arch	core	hwpl	fwpl	hwdz	hwpl	fwdz
Simple Lithology	qtz vein	qtz sst	qtz sst	min qtz sst	ox qtz sst	ox qtz sst
Unit	vein	Tw	Kmvo	Tw	Tw	Kmvo
Mineral	**Weight %**	**Weight %**	**Weight %**	**Weight %**	**Weight %**	**Weight %**
CLAYS						
Kaolinite (disordered)	0.0	1.2	0.0	0.0	6.5	0.0
Illite (1Md)	4.0	6.3	3.1	0.0	2.9	0.6
Illite (1M; R>3; 95%I)	0.0	9.8	4.1	0.0	0.6	0.0
Illite (1M; RM30)	1.3	2.8	12.7	0.0	8.8	11.6
Glauconite	0.0	0.2	0.0	0.0	0.0	0.0
Biotite (1M)	0.0	0.0	0.0	0.0	0.0	0.0
Phlogopite (2M1)	0.0	0.0	0.0	0.0	0.0	0.0
Chlorite (CCa-2)	0.0	2.5	1.6	0.0	0.0	0.0
Chlorite (CMM)	0.0	1.2	0.0	0.0	0.0	0.0
Chlorite (Fe-rich; Tusc)	0.0	1.0	0.0	0.0	0.0	0.0
Chlorite (Mg; Luzenac)	0.4	0.2	0.0	0.0	0.4	0.0
Muscovite (2M1)	4.7	3.8	6.2	0.0	11.2	19.9
Total clays	10.4	28.9	27.8	0.0	30.4	32.1
Full Pattern Degree of Fit	0.13	0.10	0.08	0.11	0.09	0.13
Pre-Normalized Total	102.7	102.5	107.1	92.6	102.5	101.0

Table 5. X-ray diffraction mineralogy for rock samples from Elk Basin, Colorado.—Cont.

[Abbreviations: USGS = U.S. Geological Survey, MRP = mineral resources program, ICPAES-MS = inductively coupled plasma-atomic emission and mass spectrometry, No. = Number, Ft = feet, std = standard, oc = outcrop, L1 = level 1 (3 and 5), fv = fault vein, m = meter, se = southeast, nw = northwest, flt = fault, B8 = borehole 8, WGS84 = world geodetic survey 1984 (all GPS data uses this coordiante system), dd= decimal degrees, Z = elevation above dataum, PDOP = positional (3D) dilution of precision, Arch = arcitecture, hw = hanging wall, pl = protolith, fw = footwall, dz = damage zone, qtz = quartz, sst = sandstone, min= mineralized, arg = argillized, ox = oxidized, Kmvo = Upper Cretaceous Ohio Creek, cata = cataclasite, CRG = clay-rich gouge, py = pyrite, unox = unoxidized, polymet = polymetallic, Tw = Tertiary Wasatch, Tqmp = Tertiary quartz monzonite porphry, % = percent, ppm = parts per million]

USGS Lab No.	C-327503	C-327504	C-327505	C-327506	C-327507	C-327508
Sample No.	**70909 14A**	**70909 14B**	**70909 14C**	**70909 14D**	**72009 1A**	**72109 3A**
Location	std mine L3, fv, ~100m nw of flt	std mine L3, fv, ~2m nw of flt	std mine L3, fv, ~2m se of flt	std mine L3, fv, ~20m se of flt	std mine oc	std mine L3, fv, 7m n of MSTD34
LON (dd)	–107.071	–107.070	–107.070	–107.070	–107.076	–107.070
LAT (dd)	38.883	38.882	38.882	38.882	38.878	38.883
Z (m)	3,440.6	3,440.6	3,440.6	3,440.6	3,356.6	3,440.6
PDOP	2.7	2.7	2.7	2.7	2.4	na
Fault Arch	fwpl	fwdz	hwdz	hwpl	fwpl	core
Simple Lithology	qtz sst	qtz sst	qtz sst	qtz sst	porphry	Kmvo cata
Unit	Kmvo	Kmvo	Tw	Tw	Tqmp	crg
Mineral	**Weight %**	**Weight %**	**Weight %**	**Weight %**	**Weight %**	**Weight %**
NON-CLAYS						
Quartz	67.4	79.8	40.1	18.9	30.2	36.5
Kspar (ordered Microcline)	8.5	0.0	0.0	0.0	0.0	0.0
Kspar (intermediate microcline)	2.2	1.2	0.6	0.9	12.7	0.0
Kspar (sanidine)	0.1	0.0	0.0	0.0	6.7	0.3
Plagioclase (albite, var. cleavelandite)	0.0	0.1	6.0	1.7	23.5	0.1
Plagioclase (oligoclase; Norway)	0.0	0.1	0.3	32.5	1.9	0.0
Plagioclase (anorthite)	0.0	0.0	0.0	12.5	0.0	0.0
Calcite	0.0	0.0	2.4	1.7	0.0	0.0
Amphibole (ferrotschermakite)	0.0	0.0	0.0	0.0	0.0	0.0
Pyrite	0.0	0.0	0.0	0.0	0.4	0.2
Hematite	0.0	0.0	0.0	0.1	0.0	0.0
Goethite	0.0	0.6	0.0	0.0	0.1	0.0
Fluorapatite	0.0	0.0	0.0	0.2	0.5	0.2
Galena	0.0	0.0	0.0	0.1	0.0	0.1
Jarosite (Mex)	0.0	1.3	0.0	0.8	0.5	0.0
Sphalerite	0.0	0.0	0.0	0.0	0.0	0.1
Anglesite	0.0	0.0	0.1	0.4	0.2	0.1
Total non-clays	78.3	83.1	49.6	69.7	76.6	37.6

Table 5. X-ray diffraction mineralogy for rock samples from Elk Basin, Colorado.—Cont.

[Abbreviations: USGS = U.S. Geological Survey, MRP = mineral resources program, ICPAES-MS = inductively coupled plasma-atomic emission and mass spectrometry, No. = Number, Ft = feet, std = standard, oc = outcrop, L1 = level 1 (3 and 5), fv = fault vein, m = meter, se = southeast, nw = northwest, flt = fault, B8 = borehole 8, WGS84 = world geodetic survey 1984 (all GPS data uses this coordiante system), dd= decimal degrees, Z = elavation above dataum, PDOP = positional (3D) dilution of precision, Arch = arcitecture, hw = hanging wall, pl = protolith, fw = footwall, dz = damage zone, qtz = quartz, sst = sandstone, min= mineralized, arg = argillized, ox = oxidized, Kmvo = Upper Cretaceous Ohio Creek, cata = cataclasite, CRG = clay-rich gouge, py = pyrite, unox = unoxidized, polymet = polymetallic, Tw = Tertiary Wasatch, Tqmp = Tertiary quartz monzonite porphry, % = percent, ppm = parts per million]

USGS Lab No.	C-327503	C-327504	C-327505	C-327506	C-327507	C-327508
Sample No.	**70909 14A**	**70909 14B**	**70909 14C**	**70909 14D**	**72009 1A**	**72109 3A**
Location	std mine L3, fv, ~100m nw of flt	std mine L3, fv, ~2m nw of flt	std mine L3, fv, ~2m se of flt	std mine L3, fv, ~20m se of flt	std mine oc	std mine L3, fv, 7m n of MSTD34
LON (dd)	–107.071	–107.070	–107.070	–107.070	–107.076	–107.070
LAT (dd)	38.883	38.882	38.882	38.882	38.878	38.883
Z (m)	3,440.6	3,440.6	3,440.6	3,440.6	3,356.6	3,440.6
PDOP	2.7	2.7	2.7	2.7	2.4	na
Fault Arch	fwpl	fwdz	hwdz	hwpl	fwpl	core
Simple Lithology	qtz sst	qtz sst	qtz sst	qtz sst	porphry	Kmvo cata
Unit	Kmvo	Kmvo	Tw	Tw	Tqmp	crg
Mineral	**Weight %**	**Weight %**	**Weight %**	**Weight %**	**Weight %**	**Weight %**
CLAYS						
Kaolinite (disordered)	0.2	0.3	0.0	0.9	0.0	1.9
Illite (1Md)	0.9	2.5	4.5	10.5	4.6	12.6
Illite (1M; R>3; 95%I)	3.5	0.0	10.6	3.1	3.2	12.2
Illite (1M; RM30)	4.9	4.5	4.5	0.0	4.2	8.4
Glauconite	0.0	0.0	0.6	0.6	0.1	0.0
Biotite (1M)	0.0	0.0	0.0	0.0	0.0	0.0
Phlogopite (2M1)	0.0	0.0	0.0	0.0	0.0	0.0
Chlorite (CCa-2)	0.0	0.0	9.0	3.2	4.2	0.5
Chlorite (CMM)	0.0	0.0	2.6	3.1	3.0	0.0
Chlorite (Fe-rich; Tusc)	0.0	0.0	0.6	2.0	2.1	0.0
Chlorite (Mg; Luzenac)	0.0	0.0	0.1	0.5	0.0	0.3
Muscovite (2M1)	12.2	9.5	17.8	6.4	2.0	26.5
Total clays	21.7	16.9	50.4	30.3	23.4	62.4
Full Pattern Degree of Fit	0.09	0.11	0.09	0.11	0.08	0.08
Pre-Normalized Total	107.5	103.8	105.3	104.1	97.4	106.2

Table 5. X-ray diffraction mineralogy for rock samples from Elk Basin, Colorado.—Cont.

[Abbreviations: USGS = U.S. Geological Survey, MRP = mineral resources program, ICPAES-MS = inductively coupled plasma-atomic emission and mass spectrometry, No. = Number, Ft = feet, std = standard, oc = outcrop, L1 = level 1 (3 and 5), fv = fault vein, m = meter, se = southeast, nw = northwest, flt = fault, B8 = borehole 8, WGS84 = world geodetic survey 1984 (all GPS data uses this coordiante system), dd= decimal degrees, Z = elevation above dataum, PDOP = positional (3D) dilution of precision, Arch = arcitecture, hw = hanging wall, pl = protolith, fw = footwall, dz = damage zone, qtz = quartz, sst = sandstone, min= mineralized, arg = argillized, ox = oxidized, Kmvo = Upper Cretaceous Ohio Creek, cata = cataclasite, CRG = clay-rich gouge, py = pyrite, unox = unoxidized, polymet = polymetallic, Tw = Tertiary Wasatch, Tqmp = Tertiary quartz monzonite porphry, % = percent, ppm = parts per million]

USGS Lab No.	**C-327509**	**C-327510**	**C-327511**	**C-327512**	**C-327513**	**C-327514**
Sample No.	**72109 4A**	**72209 1A**	**72209 1B**	**72209 1C**	**72209 10A**	**72209 11A**
Location	std mine L3, fv, ec-mstdl35, n end tunnel	std mine L5, fv, 168ft ne of portal	std mine L5, fv, 168ft ne of portal, ~1m from core	std mine L5, fv, 197ft ne of portal, ~1m from core	elk basin oc	elk basin oc
LON (dd)	–107.070	–107.068	–107.068	–107.068	–107.068	–107.067
LAT (dd)	38.883	38.883	38.883	38.883	38.883	38.886
Z (m)	3,440.6	3,360.8	3,360.8	3,360.8	3,526.5	3,559.5
PDOP	na	na	na	na	na	na
Fault Arch	core	core	fwdz	hwdz	hwpl	fwpl
Simple Lithology	crg	py crg	qtz sst	qtz sst	unox qtz sst	ox qtz sst
Unit	crg	crg	Kmvo	Tw	Tw	Kmvo
Mineral	**Weight %**	**Weight %**	**Weight %**	**Weight %**	**Weight %**	**Weight %**
NON-CLAYS						
Quartz	21.3	39.1	70.7	44.4	22.9	53.8
Kspar (ordered Microcline)	0.0	0.0	1.1	0.0	0.0	5.2
Kspar (intermediate microcline)	0.0	0.0	0.9	0.0	0.0	3.3
Kspar (sanidine)	0.6	0.4	0.4	0.4	0.0	0.3
Plagioclase (albite, var. cleavelandite)	0.0	0.0	0.0	0.4	0.8	11.8
Plagioclase (oligoclase; Norway)	0.0	0.0	0.0	0.0	23.8	1.9
Plagioclase (anorthite)	0.0	0.0	0.0	0.0	12.3	0.0
Calcite	0.0	0.0	0.0	2.5	1.0	3.9
Amphibole (ferrotschermakite)	0.0	0.0	0.0	0.0	0.0	0.0
Pyrite	2.1	1.7	1.0	1.6	0.6	0.2
Hematite	0.0	0.0	0.0	0.0	0.2	0.0
Goethite	0.6	0.0	0.0	0.0	0.0	0.0
Fluorapatite	1.2	0.0	0.0	0.4	0.2	0.1
Galena	0.1	0.0	0.0	0.0	0.2	0.0
Jarosite (Mex)	0.0	0.0	0.2	0.0	0.3	0.0
Sphalerite	0.1	0.2	0.1	0.1	0.0	0.0
Anglesite	0.2	0.0	0.0	0.3	0.3	0.0
Total non-clays	26.0	41.4	74.4	50.2	62.4	80.4

Table 5. X-ray diffraction mineralogy for rock samples from Elk Basin, Colorado.—Cont.

[Abbreviations: USGS = U.S. Geological Survey, MRP = mineral resources program, ICPAES-MS = inductively coupled plasma-atomic emission and mass spectrometry, No. = Number, Ft = feet, std = standard, oc = outcrop, L1 = level 1 (3 and 5), fv = fault vein, m = meter, se = southeast, nw = northwest, flt = fault, B8 = borehole 8, WGS84 = world geodetic survey 1984 (all GPS data uses this coordiante system), dd= decimal degrees, Z = elavation above dataum, PDOP = positional (3D) dilution of precision, Arch = arcitecture, hw = hanging wall, pl = protolith, fw = footwall, dz = damage zone, qtz = quartz, sst = sandstone, min= mineralized, arg = argillized, ox = oxidized, Kmvo = Upper Cretaceous Ohio Creek, cata = cataclasite, CRG = clay-rich gouge, py = pyrite, unox = unoxidized, polymet = polymetallic, Tw = Tertiary Wasatch, Tqmp = Tertiary quartz monzonite porphry, % = percent, ppm = parts per millio].

USGS Lab No.	C-327509	C-327510	C-327511	C-327512	C-327513	C-327514
Sample No.	72109 4A	72209 1A	72209 1B	72209 1C	72209 10A	72209 11A
Location	std mine L3, fv, ec-mstdl35, n end tunnel	std mine L5, fv, 168ft ne of portal	std mine L5, fv, 168ft ne of portal, ~1m from core	std mine L5, fv, 197ft ne of portal, ~1m from core	elk basin oc	elk basin oc
LON (dd)	–107.070	–107.068	–107.068	–107.068	–107.068	–107.067
LAT (dd)	38.883	38.883	38.883	38.883	38.883	38.886
Z (m)	3,440.6	3,360.8	3,360.8	3,360.8	3,526.5	3,559.5
PDOP	na	na	na	na	na	na
Fault Arch	core	core	fwdz	hwdz	hwpl	fwpl
Simple Lithology	crg	py crg	qtz sst	qtz sst	unox qtz sst	ox qtz sst
Unit	crg	crg	Kmvo	Tw	Tw	Kmvo
Mineral	**Weight %**	**Weight %**	**Weight %**	**Weight %**	**Weight %**	**Weight %**
CLAYS						
Kaolinite (disordered)	1.3	0.0	0.0	1.2	0.1	0.0
Illite (1Md)	13.8	17.4	0.0	0.0	0.6	1.2
Illite (1M; R>3; 95%I)	13.7	2.6	3.0	17.8	9.2	6.1
Illite (1M; RM30)	13.9	5.3	4.7	5.8	0.0	3.7
Glauconite	0.0	0.0	0.0	0.3	0.7	0.0
Biotite (1M)	0.0	0.0	0.0	0.0	0.0	0.0
Phlogopite (2M1)	0.0	0.0	0.0	0.0	0.0	0.0
Chlorite (CCa-2)	0.0	0.0	0.0	6.9	7.0	1.0
Chlorite (CMM)	0.0	0.0	0.0	0.5	6.9	0.8
Chlorite (Fe-rich; Tusc)	0.0	0.0	0.0	0.0	5.8	0.0
Chlorite (Mg; Luzenac)	1.3	1.4	0.3	0.6	0.3	0.0
Muscovite (2M1)	29.8	32.0	17.6	16.6	6.8	6.8
Total clays	74.0	58.6	25.6	49.8	37.6	19.6
Full Pattern Degree of Fit	0.09	0.11	0.13	0.10	0.11	0.09
Pre-Normalized Total	99.0	101.5	95.8	101.1	101.3	95.8

Table 5. X-ray diffraction mineralogy for rock samples from Elk Basin, Colorado.—Cont.

[Abbreviations: USGS = U.S. Geological Survey, MRP = mineral resources program, ICPAES-MS = inductively coupled plasma-atomic emission and mass spectrometry, No. = Number, Ft = feet, std = standard, oc = outcrop, L1 = level 1 (3 and 5), fv = fault vein, m = meter, se = southeast, nw = northwest, flt = fault, B8 = borehole 8, WGS84 = world geodetic survey 1984 (all GPS data uses this coordiante system), dd= decimal degrees, Z = elavation above dataum, PDOP = positional (3D) dilution of precision, Arch = arcitecture, hw = hanging wall, pl = protolith, fw = footwall, dz = damage zone, qtz = quartz, sst = sandstone, min= mineralized, arg = argillized, ox = oxidized, Kmvo = Upper Cretaceous Ohio Creek, cata = cataclasite, CRG = clay-rich gouge, py = pyrite, unox = unoxidized, polymet = polymetallic, Tw = Tertiary Wasatch, Tqmp = Tertiary quartz monzonite porphry, % = percent, ppm = parts per million]

USGS Lab No.	**C-327515**	**C-327516**	**C-327517**	**C-327518**
Sample No.	**72209 14A**	**72409 43A**	**B8 75 ft**	**B8 113 ft**
Location	elk basin oc	elk fault oc sw tip	std drill core B8	std drill core B8
LON (dd)	–107.071	–107.078	–107.072	–107.072
LAT (dd)	38.880	38.880	38.881	38.881
Z (m)	3,405.3	3,435.5	3,415.5	3,415.5
PDOP	na	na	0.1 (m)	0.1 (m)
Fault Arch	hwpl	hwdz	fwdz	fwdz
Simple Lithology	unox porphyry	arg Tw	qtz sst	polymet vein
Unit	Tqmp	Tw veins	Kmvo	Kmvo
Mineral	**Weight %**	**Weight %**	**Weight %**	**Weight %**
NON-CLAYS				
Quartz	23.0	57.9	73.7	7.6
Kspar (ordered Microcline)	0.9	0.0	0.0	0.0
Kspar (intermediate microcline)	12.1	0.0	0.8	0.4
Kspar (sanidine)	6.0	0.1	0.0	0.0
Plagioclase (albite, var. cleavelandite)	20.3	0.0	0.2	0.5
Plagioclase (oligoclase; Norway)	6.3	0.0	0.0	1.3
Plagioclase (anorthite)	0.2	0.0	0.0	0.0
Calcite	1.3	0.0	0.0	6.7
Amphibole (ferrotschermakite)	0.0	0.0	0.2	2.5
Pyrite	0.9	0.1	4.4	56.2
Hematite	0.0	0.0	0.0	0.0
Goethite	0.0	0.0	0.0	0.0
Fluorapatite	0.6	0.0	0.9	2.4
Galena	0.0	0.0	0.2	1.0
Jarosite (Mex)	0.3	0.0	0.0	4.6
Sphalerite	0.0	0.0	0.5	9.7
Anglesite	0.3	0.0	0.0	4.9
Total non-clays	72.3	58.1	80.9	97.6

Table 5. X-ray diffraction mineralogy for rock samples from Elk Basin, Colorado.—Cont.

[Abbreviations: USGS = U.S. Geological Survey, MRP = mineral resources program, ICPAES-MS = inductively coupled plasma-atomic emission and mass spectrometry, No. = Number, Ft = feet, std = standard, oc = outcrop, L1 = level 1 (3 and 5), fv = fault vein, m = meter, se = southeast, nw = northwest, flt = fault, B8 = borehole 8, WGS84 = world geodetic survey 1984 (all GPS data uses this coordiante system), dd= decimal degrees, Z = elavation above dataum, PDOP = positional (3D) dilution of precision, Arch = arcitecture, hw = hanging wall, pl = protolith, fw = footwall, dz = damage zone, qtz = quartz, sst = sandstone, min= mineralized, arg = argillized, ox = oxidized, Kmvo = Upper Cretaceous Ohio Creek, cata = cataclasite, CRG = clay-rich gouge, py = pyrite, unox = unoxidized, polymet = polymetallic, Tw = Tertiary Wasatch, Tqmp = Tertiary quartz monzonite porphry, % = percent, ppm = parts per million]

USGS Lab No.	C-327515	C-327516	C-327517	C-327518
Sample No.	**72209 14A**	**72409 43A**	**B8 75 ft**	**B8 113 ft**
Location	elk basin oc	elk fault oc sw tip	std drill core B8	std drill core B8
LON (dd)	–107.071	–107.078	–107.072	–107.072
LAT (dd)	38.880	38.880	38.881	38.881
Z (m)	3,405.3	3,435.5	3,415.5	3,415.5
PDOP	na	na	0.1 (m)	0.1 (m)
Fault Arch	hwpl	hwdz	fwdz	fwdz
Simple Lithology	unox porphyry	arg Tw	qtz sst	polymet vein
Unit	Tqmp	Tw veins	Kmvo	Kmvo
Mineral	**Weight %**	**Weight %**	**Weight %**	**Weight %**
CLAYS				
Kaolinite (disordered)	0.0	0.0	0.4	0.0
Illite (1Md)	0.0	4.4	2.4	0.0
Illite (1M; R>3; 95%I)	10.5	10.9	0.0	0.0
Illite (1M; RM30)	0.0	10.1	9.2	0.0
Glauconite	1.7	0.0	0.0	0.0
Biotite (1M)	0.0	0.0	0.0	1.1
Phlogopite (2M1)	0.1	0.0	0.0	1.1
Chlorite (CCa-2)	4.3	0.1	0.0	0.0
Chlorite (CMM)	4.0	0.0	0.0	0.0
Chlorite (Fe-rich; Tusc)	0.0	0.0	0.0	0.2
Chlorite (Mg; Luzenac)	0.0	0.1	0.0	0.0
Muscovite (2M1)	7.1	16.4	7.1	0.0
Total clays	27.7	41.9	19.1	2.4
Full Pattern Degree of Fit	0.10	0.10	0.12	0.15
Pre-Normalized Total	102.2	101.1	93.2	100.1

Observations and Data

Map to Sample Scale Features

Stratigraphy, Bedforms, Lithologic Contacts, and Geomorphology

Within Elk Basin, the Ohio Creek Member and Wasatch Formation are generally as were mapped by Gaskill and others (1967) (figs. 6 and 7). No stratigraphic sections were measured; however, a few pertinent observations were noted.

1. The Ohio Creek shows numerous cross-bedded sequences at scales of several centimeters to decimeters as well as various channel-fill bedforms and some planar bedding at scales of tens of meters (fig. 8).
2. Sedimentary bedforms in the Wasatch are curviplanar to lenticular throughout scales of tens of meters and greater with some local cross bedding.
3. Although the predominant lithology in both the Ohio Creek and Wasatch is siliciclastic sandstone, carbonaceous shale forms numerous and complex interlayers in the Ohio Creek and laterally continuous shale beds and conglomeratic lenses in the Wasatch.
4. Bedding in both Ohio Creek and Wasatch dip gently (10°–20°) to the south and southwest (fig. 9).
5. Stratigraphic formation contacts were not found; however, unit contacts in each formation are generally curviplanar and where channel fill exists there has clearly been erosion. Talus and other surface deposits lie unconformably and nonuniformly on bedrock.
6. The geomorphology of the upper Elk Basin is fundamentally glacial and in the form of a horseshoe-shaped cirque.

However, there are numerous “stratigraphic” benches that form a stepped structure to the cirque floor, and this complex surface has been sharply incised by Elk Creek and other lower order stream channels (fig. 5). Some of these benches are cut by meter-wide ribs formed by quartz veins, some wider than 10 m, primarily in the northeastern portion of the upper basin (fig. 10). The Standard and Elk fault veins form first order, subparallel drainage channels. Where the perennial Elk Creek emerges it flows parallel and adjacent to the Elk fault vein on its footwall side. Elk Creek crosses between the Elk and Standard fault veins running south then crosses the Standard (fig. 7). An apparently inactive ephemeral channel has also formed adjacent to part of the surface trace of the Standard fault vein (fig. 7).

Spot Mineralogy, Petrography, and Alteration

Figure 11 is a geologic map showing the locations of approximately 150 spot mineralogy determinations in the upper Elk Basin. At these localities hand sample mineralogy was determined and two fundamental observations were recorded.

1. The Ohio Creek Member is leached of pyrite nearly everywhere in at least the upper meter of outcrop. Evidence for this leaching is from hand lens observations of pervasive, disseminated cubic holes with orange-red, presumably iron-oxide, staining in the Ohio Creek matrix. The only place leaching was not observed was adjacent to polymetallic quartz veins as shown on Figure 12.
2. Where pyrite occurs in the Wasatch Formation it was fresh on freshly broken surfaces and slightly weathered on exposed surfaces. Although pyrite is disseminated in Wasatch, its distribution is not uniform.

Standard size thin sections from surface outcrops of Ohio Creek quartz sandstones show subrounded to rounded grains of quartz, calcic plagioclase, potassium feldspar, muscovite, chert, some lithic fragments, and clots of organic-rich clay (fig. 13). No evidence of silicification was observed. Many feldspars are fresh and some, particularly potassium feldspars, are pseudomorphically replaced by sericite. Pervasive sericite and clays indicate weak argillic hydrothermal alteration (fig. 13). Minor to moderate amounts of calcite are found as a late pore space infill. The pore structure is generally tight with the exception of numerous but isolated holes ranging from about 100s of microns to millimeters in size. Some of these holes have iron oxide staining around them, and the few pseudomorphic grains of what likely was pyrite have been transformed into translucent cubes of iron oxide. One thin section from the B8 drill core at 75 ft below the ground surface shows all of the same characteristics as the surface samples except there are fresh pyrite and partially reacted pyrite grains (fig. 13).

The Wasatch Formation is compositionally and texturally immature (fig. 13). Thin sections of representative sandstones show subhedral to rounded grains of calcic plagioclase, quartz, and biotite; trace amounts of amphibole; and opaque minerals including euhedral pyrite. A variety of lithic fragments, opaque organic materials, and abundant clay minerals are also present. No evidence of silicification was observed and feldspars are fresh to pseudomorphically altered to sericite. Pervasive sericite, moderate amounts of disseminated pyrite and calcite, with minor chlorite is also found and indicates weak propylitic hydrothermal alteration.

Ground Surface Elevation Gradients as a Proxy for Surface and Groundwater Flow

Figure 14 shows a vector diagram overlain on the geologic and topographic map of Elk Basin. The vectors (arrows) indicate the relative magnitude (arrow length) and direction of ground surface elevation gradients computed at points on a roughly 100-m square grid from the National Elevation Dataset, 30-m Digital Elevation Model georeferenced to the Elk Basin geologic map. Although the actual direction of surface and shallow groundwater flow is unknown, this

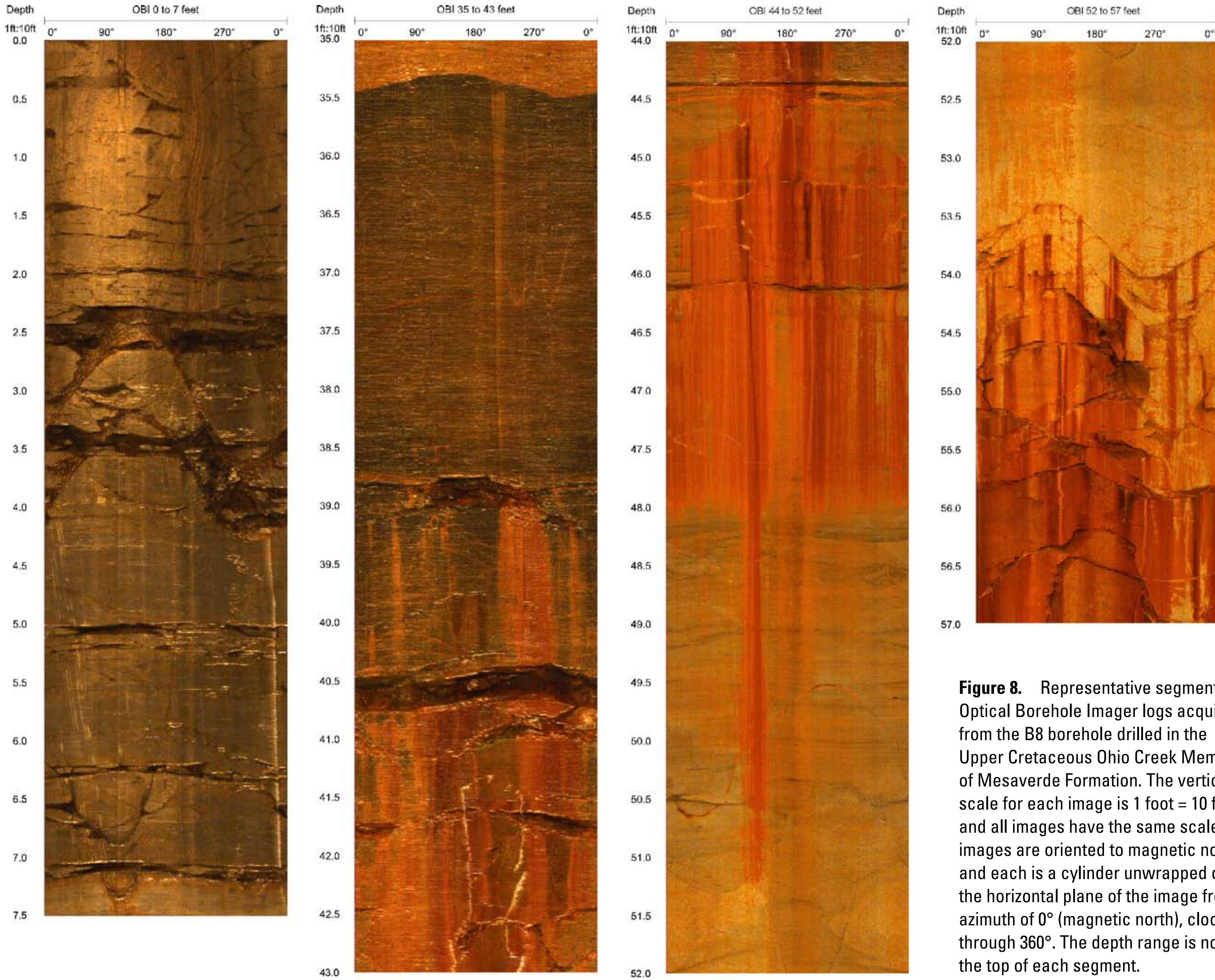


Figure 8. Representative segments of Optical Borehole Imager logs acquired from the B8 borehole drilled in the Upper Cretaceous Ohio Creek Member of Mesaverde Formation. The vertical scale for each image is 1 foot = 10 feet and all images have the same scale. The images are oriented to magnetic north and each is a cylinder unwrapped on to the horizontal plane of the image from an azimuth of 0° (magnetic north), clockwise through 360°. The depth range is noted at the top of each segment.

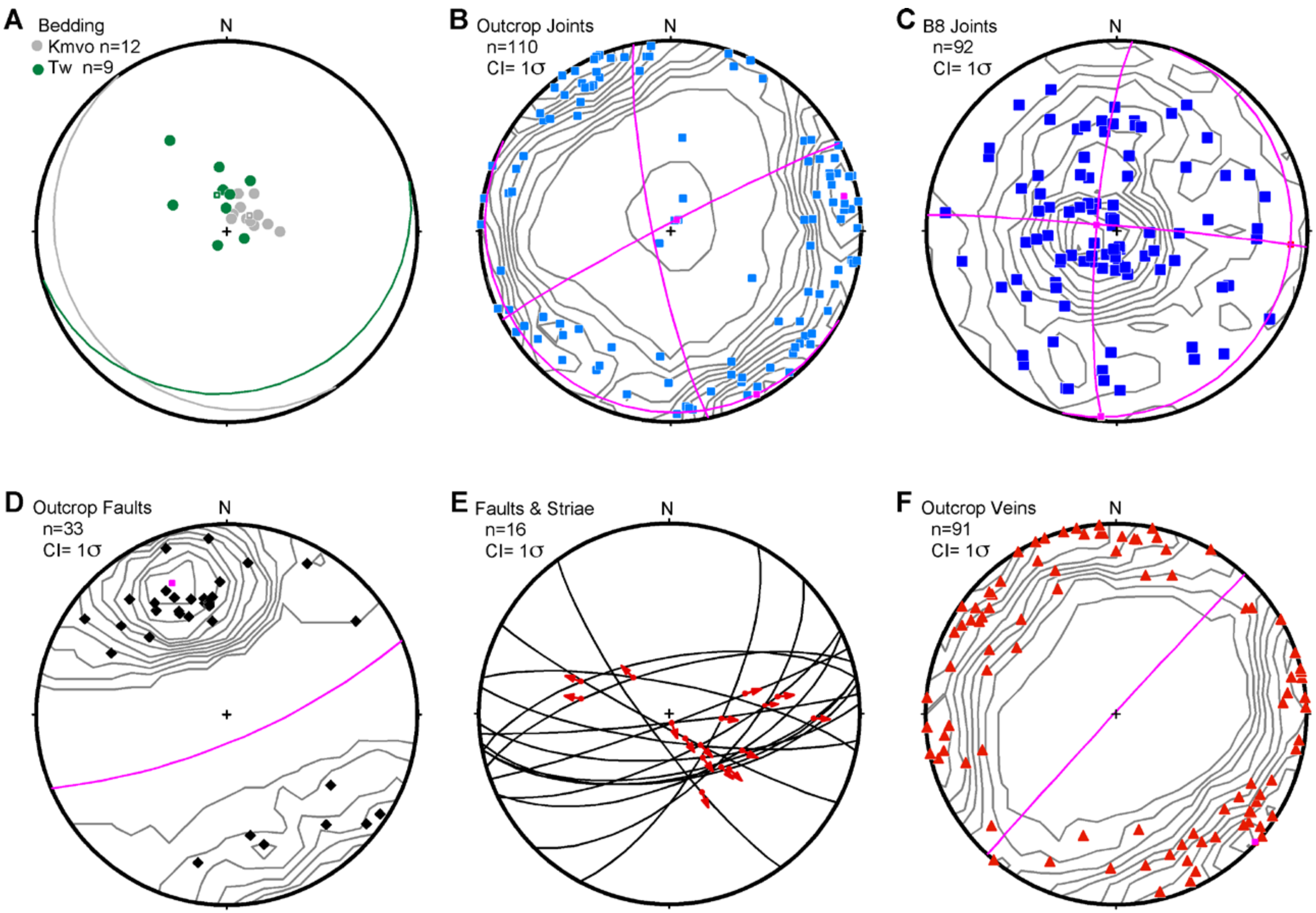


Figure 9. Lower-hemisphere, equal-area projections of structural orientation data collected in Elk Basin (n = number, CI = contour interval, and σ = standard deviation). (*A)* Poles to bedding data collected in outcrop for the Upper Cretaceous Ohio Creek Member of Mesaverde Formation (gray circles) and Tertiary Wasatch Formation (green circles). The mean great circles for each formation are shown. (*B*) Kamb contoured (gray lines) poles (blue squares) to all joints collected from outcrop (Kamb, 1959). (*C*) Kamb contoured (gray lines) poles (blue squares) to all joints measured from in the B8 borehole image log. (*D*) Kamb contoured (gray lines) poles (black diamonds) to all faults collected from outcrop. (*E*) Slip-linear diagram for faults in outcrop that have slickenlines and shear sense indicators. Each black great circle is a single fault with its slip linear shown as a red dot. The red arrows for each dot show the direction of the hanging wall relative to the footwall of each fault. (*F*) Kamb contoured (gray lines) poles (red triangles) to all quartz or polymetallic veins collected from outcrop. The mean vectors and great circles for assumed cylindrical best fits to each data set are shown in pink (see Allmendinger, 2004).

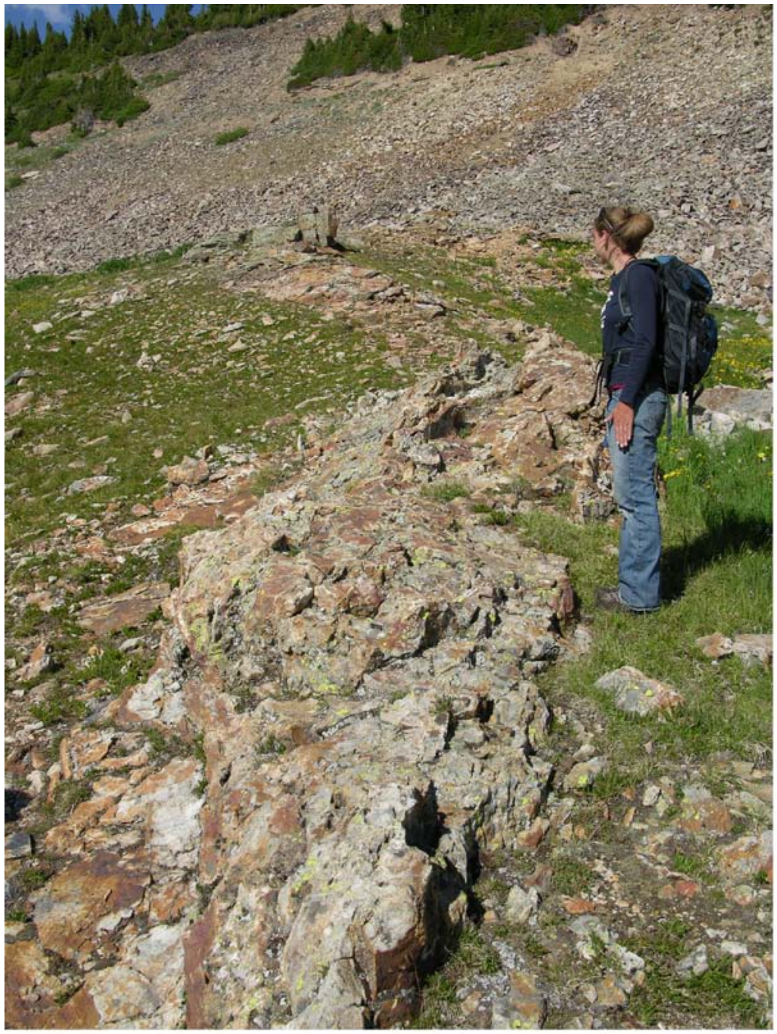


Figure 10. Photograph looking northeast at a pinching and swelling massive to stockwork barren quartz vein in the eastern portion of upper Elk Basin.

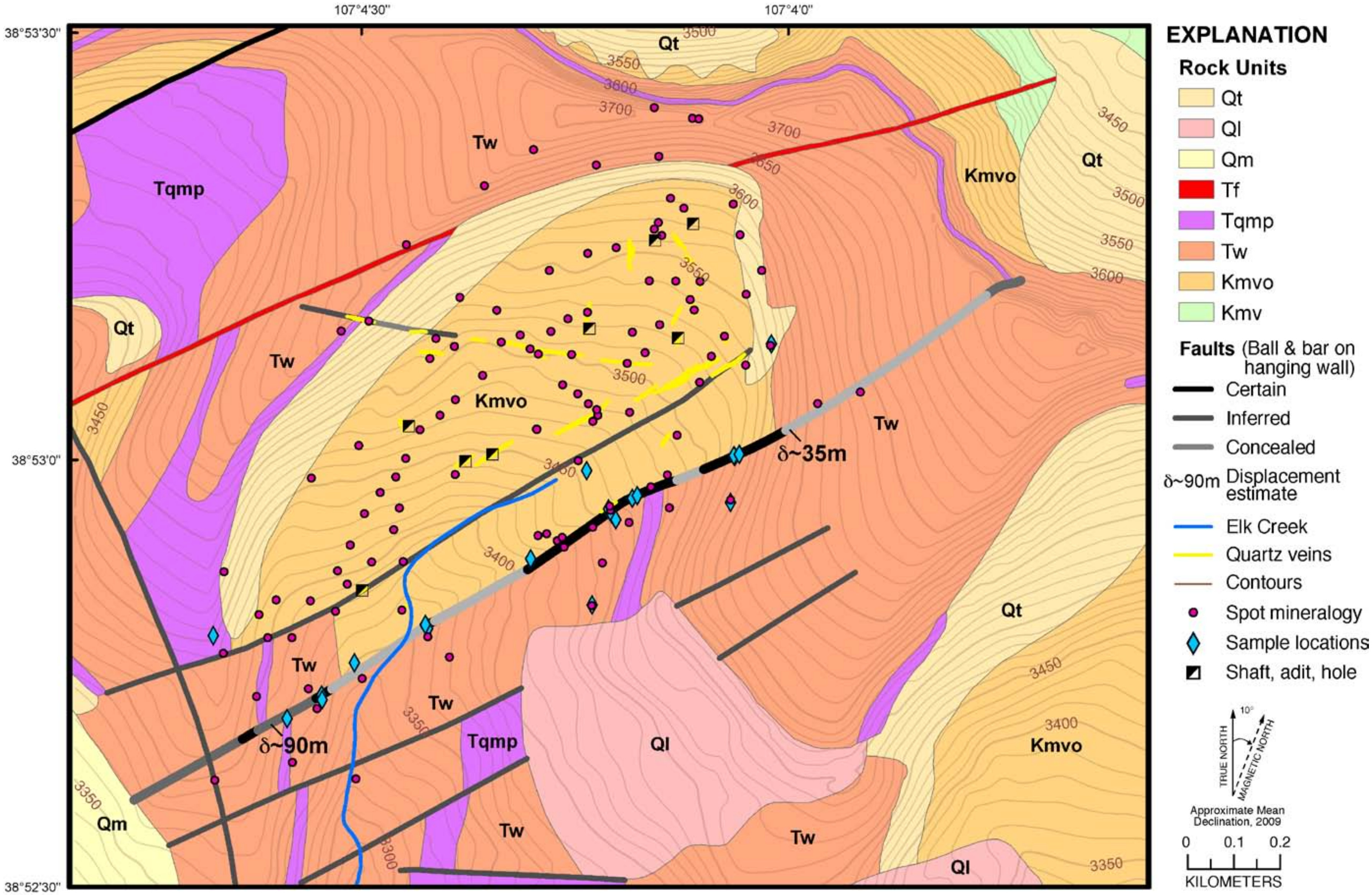


Figure 11. Reconnaissance geologic map of upper Elk Basin showing the locations of field-based spot mineralogy determinations, fault-vein rock samples, adits, shafts, dog holes, and estimates of net displacement (δ). Modified from Gaskill and others, 1967. Qt, Quaternary talus deposits; Ql, Quaternary landslide deposits; Qm, Quaternary glacial deposits; Tf, Tertiary felsite; Tqmp, Tertiary quartz monzonite porphyry; Tw, Tertiary Wasatch Formation; Kmvo, Upper Cretaceous Ohio Creek Member of Mesaverde Formation; Kmv, Upper Cretaceous Mesaverde Formation

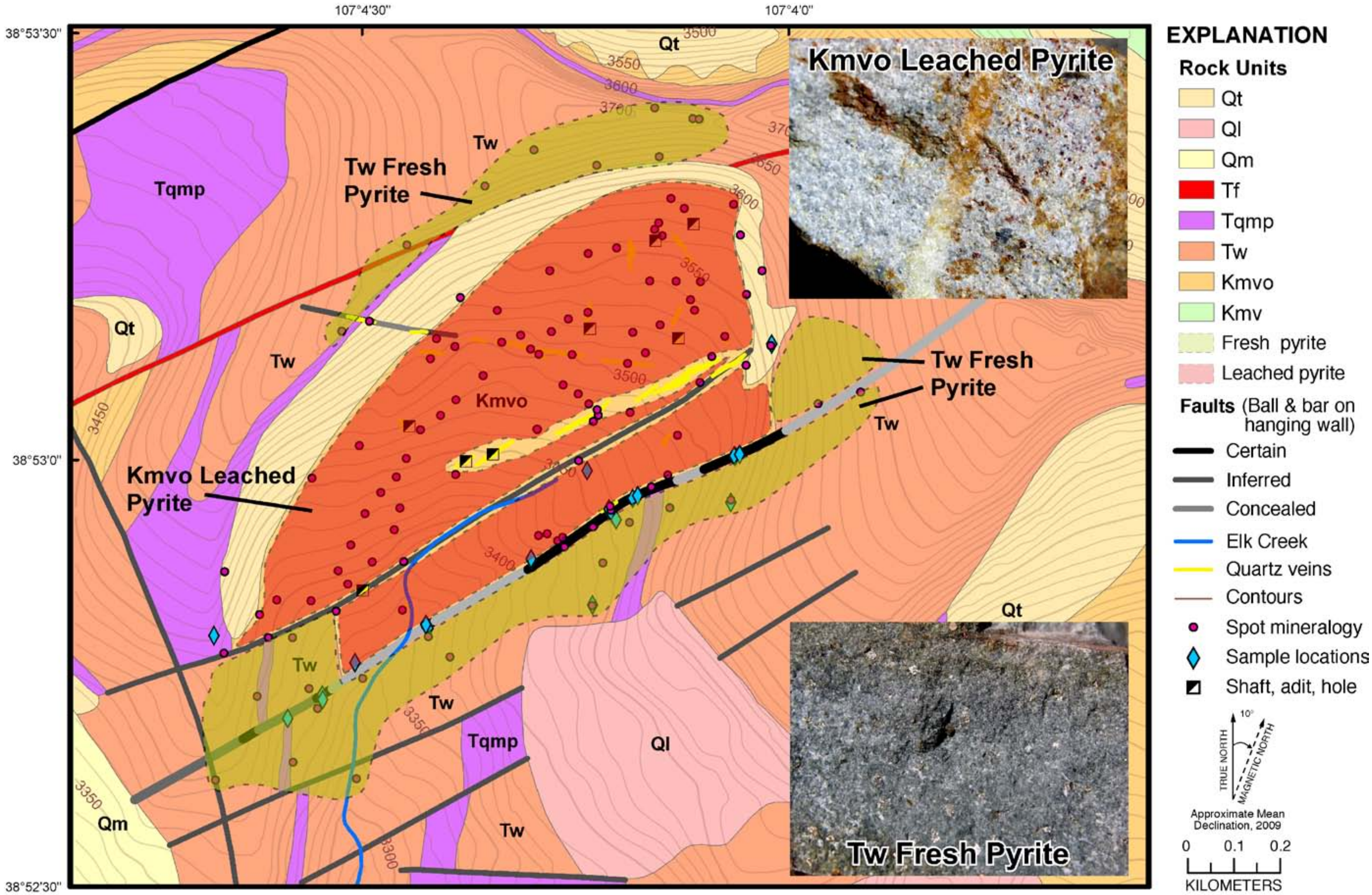


Figure 12. Reconnaissance geologic map of upper Elk Basin showing the spot mineralogy and extent of leached pyrite (orange overlay) versus fresh pyrite (light green overlay) from freshly broken hand samples from the ground surface. Photographs show examples of orange, iron oxide staining in cubic holes where pyrite likely originally resided in Ohio Creek Member (top, sample face is about 2 by 3 in) and fresh pyrite in Wasatch Formation (bottom, sample face is about 2 by 3 in). Modified from Gaskill and others, 1967. Qt, Quaternary talus deposits; Ql, Quaternary landslide deposits; Qm, Quaternary glacial deposits; Tf, Tertiary felsite; Tqmp, Tertiary quartz monzonite porphyry; Tw, Tertiary Wasatch Formation; Kmvo, Upper Cretaceous Ohio Creek Member of Mesaverde Formation; Kmv, Upper Cretaceous Mesaverde Formation.

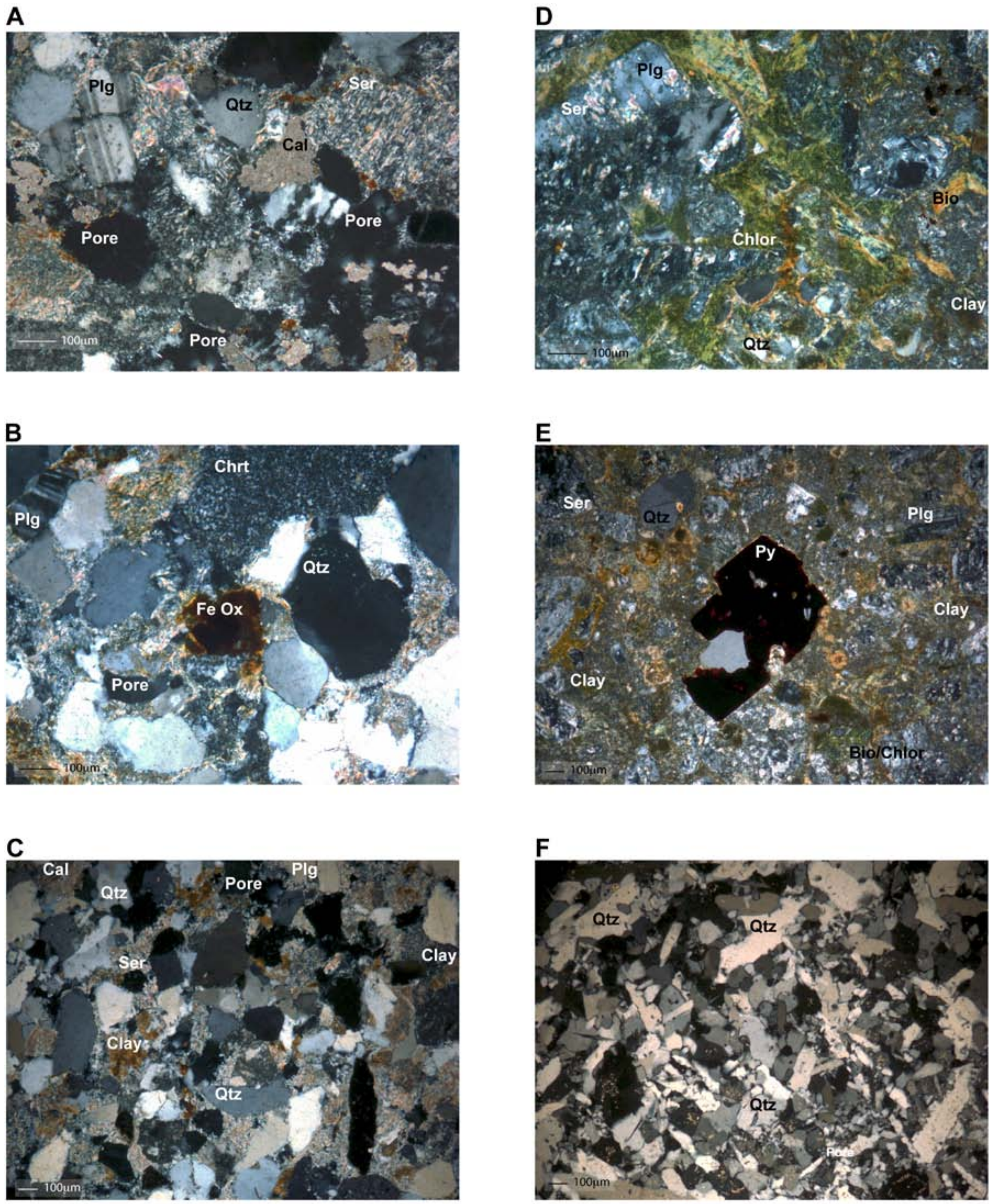


Figure 13. Thin section photomicrographs of representative outcrop samples from Elk Basin. (*A*) Ohio Creek Member of Mesaverde Formation footwall protolith sandstone, about 20 m northwest of the Standard fault vein near the Level 1 portal (sample 70909 7A). (*B*) Ohio Creek Member footwall protolith sandstone, about 100 m northwest of the Standard fault vein at the Level 3 portal (sample 70909 14A). (*C*) B8 drill core Ohio Creek footwall protolith sandstone, about 3 m northwest of the Standard fault vein below the Level 2 portal from 23 m below ground surface, 5x magnification (sample B8 75 Feet). (*D*) and (*E*) Wasatch Formation hanging wall protolith sandstone, about 80 m southeast of the Standard fault vein between the Level 4 and 5 portals, view (*E*) is 5x magnification (sample 72209 10A). (*F*) Wasatch Formation hanging wall damage and mineralized zone, about 1 meter southeast of the Standard fault vein at the Level 1 portal, 5x magnification (sample 72209 10A). Abbreviations include: Qtz = quartz, Plg = plagioclase feldspar, Cal = calcite, Pore = pore space, Chrt = chert, Clay = unidentified clay minerals, Fe Ox = iron oxidation, Py = pyrite, Chlor = chlorite. Scale bars are show at the bottom of each image, all images use crossed polarized light and are 10x magnification unless noted.

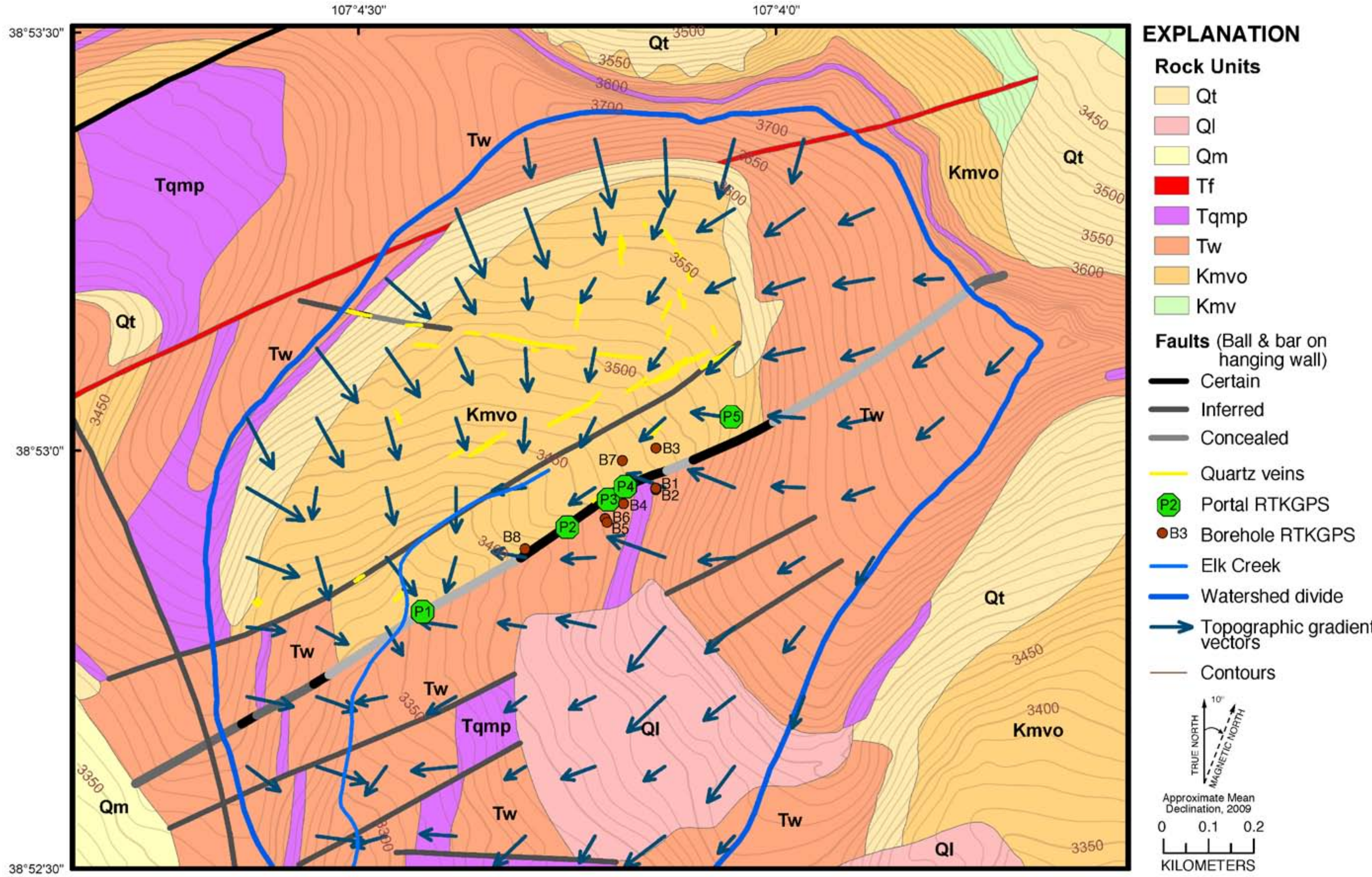


Figure 14. Revised reconnaissance geologic map of upper Elk Basin showing the watershed divide, ground surface topographic gradient field calculated along a about 100-m square grid (blue arrows with length proportional to the magnitude of the gradient), mine portal (PX, purple hexagons), and monitoring borehole (BX, brown dots) locations determined from Real Time Kinematic GPS data. Modified from Gaskill and others, 1967. Qt, Quaternary talus deposits; Ql, Quaternary landslide deposits; Qm, Quaternary glacial deposits; Tf, Tertiary felsite; Tqmp, Tertiary quartz monzonite porphyry; Tw, Tertiary Wasatch Formation; Kmvo, Upper Cretaceous Ohio Creek Member of Mesaverde Formation; Kmv, Upper Cretaceous Mesaverde Formation.

diagram shows the potential direction that this water might flow. Surface water includes water that flows directly on bedrock pavements and in the many low order stream channels and rivulets on top of surficial deposits and soils (“runoff”). By “shallow groundwater” we mean groundwater within the unconsolidated surficial deposits and the uppermost bedrock (to depths of about 3 m) that is either perched or at the very top of the saturated zone. The flow direction of surface and shallow groundwater would almost certainly deviate on a local scale from that shown in figure 14 owing to obstruction by physical features, such as large quartz veins, and by variations in the permeability of surficial deposits and shallow bedrock. However, figure 14 serves as a reasonable approximation of the general direction of surface and shallow groundwater flow on the larger scale of an entire hillslope. Further discussion related to figure 14 refers to the assumed surface and shallow groundwater flow direction depicted on the figure as “shallow flow”The computed gradient field shows that shallow flow moves from the crest of the cirque inward and downhill with semiradial convergence between the ground surface traces of the Elk and Standard fault veins (fig. 14). Most vectors above the Level 1 portal are parallel to the Standard fault-vein trace in the footwall or trend into the fault vein on the hanging wall side. Figure 14 shows that an appreciable number of vectors that intersect with the Standard fault vein originate from the Wasatch hanging wall side as well as the Ohio Creek footwall side. It should be kept in mind that the actual direction of groundwater flow may be considerably different than shown figure 14, particularly the deeper groundwater flow field which may be more influenced by the larger, watershed-scale topography and less by the detailed near-surface topography.

Petrophysics

Table 3 shows the results of the MICP measurements. It is critical to remember that these data apply only to the intergranular properties of the rock samples and do not reflect the macroscopic fracture network-related porosity or permeability (hydraulic conductivity) because macroscopic fractures are not sampled with this method. The Ohio Creek surface outcrop sample has a porosity of 9.2 percent and estimated hydraulic conductivity of 8.4×10^{-10} m/s, the clay-rich gouge sample from the Standard fault vein from Level 3 in the Standard Mine has a porosity of 21.3 percent and estimated hydraulic conductivity of 3.5×10^{-11} m/s, and the Wasatch surface outcrop sample has a porosity of 0.7 percent and estimated hydraulic conductivity of 1.6×10^{-15} m/s.

Geologic Structures

Joints and Televiewer Log Data

The sedimentary and intrusive bedrock in Elk Basin are pervasively jointed. These joints are open cracks that cut all other geological features in the watershed except clay-rich fault gouge observed in the mine workings. There are three major joint set orientations. Although the set orientations are highly disperse, two sets are subparallel to regional joint sets: a nearly vertical northeast set and a north-northwest striking set. These sets are mutually crosscutting and orthogonal to suborthogonal as measured primarily in individual outcrops (fig. 9). In Elk Basin the northeast set appears to predominate. Other joint properties such as intensity (number of joints per unit line length), trace length, shape, and aperture also are quite variable. No scanline or other quantification of these properties was attempted; however, reconnaissance measurements showed that the intensity of each vertical set was on the order of 1 joint per 30 to 80 cm and that trace lengths were 2 to 5 m. These joints are generally planar to curviplanar with open but unmeasured apertures whose permeable nature is inferred from their nearly pervasive iron staining compared with rock surfaces around them (fig. 15). Estimates of true joint aperture were made from the televiewer log and range from 0.21 to 36.8 mm for several unusually large, broken joint zones; the median was 2.7 mm for 43 measurements.

The third major joint set is a subhorizontal one that also shows great dispersion. Joints in this set are measured both in outcrops and in the borehole televiewer log (figs. 15 and 16). The borehole televiewer log offers a biased view of joint orientations, because it does not capture most near-vertical joints that are subparallel to, but do not intersect, the vertical borehole. On the other hand, joints measured in outcrop can offer a biased view of subhorizontal joints if the height of the outcrop is small. Caine and Tomusiak (2003) provide an exhaustive treatment of joint measurement biases. Subhorizontal joints have dips ranging from a few degrees to 30° or 40° and strikes in virtually every direction with a moderately strong cluster striking south (fig. 9). Many of these joints form parallel to bedforms, particularly crossbeds (fig. 8).

Subhorizontal joint intensity is quite heterogeneous ranging from about 1 joint per 2 to 5 cm to about 1 joint per 3 m (figs. 8 and 16). Trace lengths are on the order of tens of centimeters to several meters or more, particularly where a joint has formed along a continuous bedding feature. Subhorizontal joints are curviplanar to arcuate and many but not all of these joints are potentially permeable. Evidence for some being hydraulically conductive can be observed in the televiewer log. Figures 8 and 16 show presumably iron-oxide stains emanating from discrete joints and intervals of joint networks. These stains occur above and below the water level in the borehole at the time the log was collected. Although no attempt to quantify differences in joint network parameters between Ohio Creek and Wasatch was made, qualitative field observations indicate many fewer subhorizontal joints in Wasatch than in Ohio Creek, which may be consistent with the lack of extensive cross bedding in Wasatch.

Faults, Fault Veins, and Fault-Related Fluid Flow

Discrete principal slip surfaces (those at the footwall or hanging wall contact between the fault core and damage zone on either side of the core), fault zones, and fault veins were

Figure 15. Outcrop photograph of Ohio Creek Member of Mesaverde Formation protolith pavement in the upper central part of Elk Basin. The near-vertical joints trend northeast and subhorizontal joints can be seen along cross bedding parallel partings. The carpenters rule is 1 m long.

all observed in Elk Basin. Of 33 fault-related principal slip surfaces measured, a reasonably tight cluster of surfaces has a mean surface orientation of 067/74 (right-hand rule strike/dip) and mean slickenline lineation of 69° down from the east-northeast (fig. 9). Although most of these slip surfaces have normal shear sense, some show a minor (rake = 52°) to one showing a moderate (rake = 28°) component of sinistral strike-slip consistent with the mapped separation of the Tqmp dikes (fig. 7) which are near vertical (figs. 9 and 7).

The Standard fault-vein mean orientation from the Level 3 tunnel is 080/62 (number of measurements, n=6) with a mean normal slip lineation of 75° down from the east. In Level 5 the mean is 075/63 (n=5) with a mean normal slip lineation of 69° down from the east. These data are consistent with the slightly curviplanar surface fault trace and with a remarkably consistent dip of the footwall's principal slip surface (fig. 11). Ground surface trace lengths of mapped faults in the vicinity of Elk Basin range from about 275 m to about 1.9 km for the Standard fault vein. Although the Standard and Elk fault veins have been drawn as continuous lines on figure 6, it is unclear whether these structures are segmented, particularly at their tips as suggested by work of the Colorado Division of Reclamation, Mining, and Safety (2007) and consistent with our underground observations in Levels 3 and 5 of the Standard Mine. Of particular note were the left-stepping relays (steps or jogs between two fault segments) observed and mapped by CDRMS (2007) in Level 5 of the Standard Mine.

The net displacement on the Standard fault was estimated at two locations as noted above in the Methods section. At the southeasternmost exposure where the fault separates a vertical dike (unit Tqmp, fig. 11), the computed net displacement is approximately 90 m, top down to the southeast (fig. 11). This displacement is normal with a minor component of sinistral motion, given that the slickenline rake was 52° down from the northeast and assuming that the bulk motion is representative along this segment of the fault zone. On the basis of the assumed position of Ohio Creek–Wasatch contact just below and at the end of the Level 5 tunnel projected to the surface, the minimum net displacement is approximately 35 m, top down to the southeast. The data are insufficient to evaluate whether these differing displacements indicate a displacement gradient, as is common with normal faults.

The architecture of the Standard fault is complex and variable. The protolith bedrock on either side of the fault is pervasively jointed and numerous quartz veins are barren of metals, but small faults were not abundant. Outcrop exposures of fault-related brittle damage, such as small faults and fault-related joints, particularly between the Standard and Elk fault veins in the Ohio Creek or in the Wasatch adjacent to the Standard fault vein, did not appear to be extensive, but no effort was made to quantify the intensity of this deformation. Thick, massive, or stockwork quartz veins primarily observed in surface outcrops of Ohio Creek several meters northwest of the fault trace were not observed in the footwall in the mine tunnels. A footwall damage zone (FWDZ) in Ohio Creek was observed in only one location in a short northwesterly crosscut in the Level 3 tunnel. Although in underground exposures the

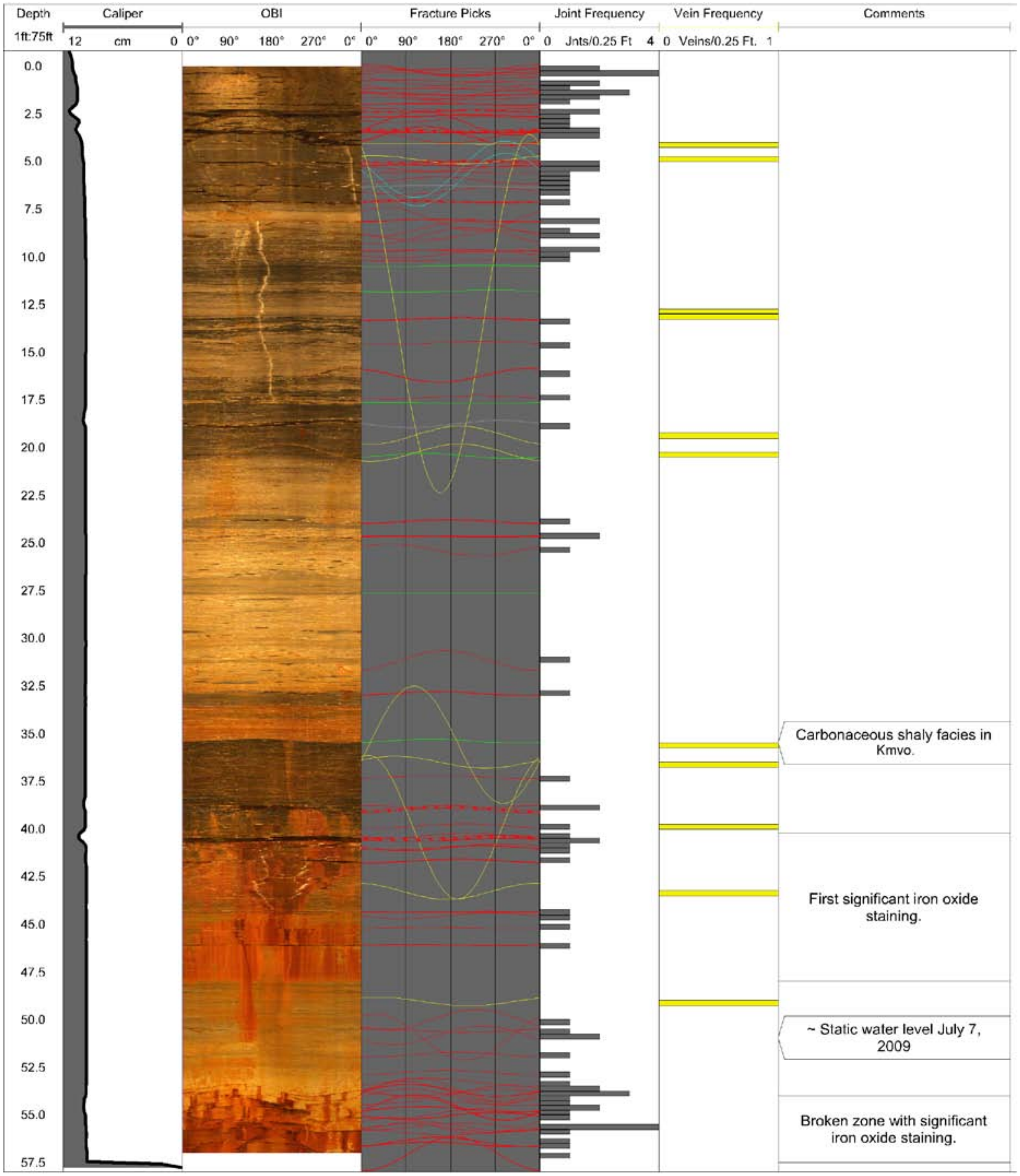


Figure 16. Borehole geophysical logs acquired from the B8 borehole. The vertical scale for each image is 1 ft = 75 ft (see fig. 8 with vertical scale of 1 ft = 10 ft). The caliper log shows the average diameter of the open borehole walls and the outer portion is shaded. The Optical Borehole Image log is oriented to magnetic north and is a cylinder unwrapped on to the horizontal plane of the image from an azimuth of 0° (magnetic north), clockwise through 360°. The Fracture Pick log shows sinusoids from each joint (red), bedding horizon (green), broken zone (blue), or vein (yellow) encountered in the borehole. Joint and vein frequency logs are simple counts of the number of features per 0.25 ft of depth in the borehole. The comment log shows a variety of interpreted features encountered in the borehole.

FWDZ did not show extensive brittle deformation or faults with gouge; a few small faults, argillic alteration, and disseminated pyrite were noted. Damage in the form of minor faults and polymetallic veins was found in the drill core from monitoring well B8 drilled into the Ohio Creek FWDZ just below the Standard Mine Level 2 portal.

Figure 17 shows photographs of possible drill-core-scale analogs for the larger scale deformation and paragenetic sequence associated with polymetallic mineralization. Figure 17A also shows minor quartz-filled fault veins where heterogeneous and unoxidized clots of pyrite, chalcopyrite, galena, and sphalerite appear to fill vugs and spaces within euhedral quartz crystals. The materials in large polymetallic veins appear to have formed within the initial euhedral-quartz veins by several segregated and successive infillings of different metals. This is shown in Figure 17. Finally, in the deeper portions of the drill core extensive oxidation and possible removal of the metals is apparent (fig. 17).

The footwall damage zone–core contact is a nearly continuous sharp, curviplanar, variably striated slip surface in both Levels 3 and 5, except at the end of Level 5 where there are relays (fig. 18). The fault core is distinctive, and at this FWDZ contact it is composed of clay and pyrite-rich fault gouge. This clay-rich seam pinches and swells in thickness but is generally a few centimeters wide. In several places the fault core structure swells to decimeters in width. Near this swelling, the core is composed of a variably thick, highly deformed, argillically altered, and locally brecciated lens of Ohio Creek with minor quartz veins and disseminated pyrite sandwiched between a second seam of pyritiferous clay-rich gouge at the contact with the hanging wall damage zone (HWDZ) and Wasatch Formation. No Wasatch was observed in these lenses and the clay gouge appeared to have primary affinity with Ohio Creek. The fault core total width was measured in numerous locations underground and ranges from 2 to 65 cm with a median of 14 cm (fig. 18). Lenses of entrained Ohio Creek are on the order of several meters long and are parallel to the strike of the master fault. Although a HWDZ occurs in the Wasatch Formation it decreased in intensity within about 1–1.5 m of the fault core-HWDZ contact, which, like the footwall, is a discrete curviplanar slip surface. The HWDZ shows numerous small faults, few veins, disseminated pyrite, and possible localized folding against the core. An argillic alteration halo associated with the Wasatch HWDZ is notably absent.

An important observation in both the Level 3 and Level 5 tunnels of the Standard Mine was that a significant amount of water was entering the mine workings asymmetrically with respect to the strike of the fault zone and was found predominantly on its footwall side (fig. 18). Some flow was entering on the hanging wall side of the fault zone, but there were many more locations of emergence and the overall magnitude of flow was significantly larger on the Ohio Creek footwall. Asymmetric flow was discrete or appeared as sheets a few meters in width. The flow emanated from the footwall damage zone contact with the footwall side of clay-rich core and possibly from fractures in the FWDZ. The footwall slip surface is coated with a large variety of precipitates, many in shades of ochre, orange, blue-green, and white (Manning and others, 2007). These surface coatings obscured the details of points of emergent flow. Very little flow emanated from within the fault core itself and at many locations with substantial flow along the footwall, the adjacent hanging wall, HWDZ and hanging wall core gouge were dry (fig. 18).

Not only is flow asymmetric at the present locations of flow along the fault zone, but deposits of flowstone are extensive. The composition of the flowstone is undetermined. These deposits are extensive and range from a few centimeters wide to several meters wide and meter-long panels. The textures range from tripe-like sheets to drapestone-like curtains. Many of the drapestone formations have a blood-red color whereas the tripe-like flowstone is commonly orange-beige to ochre. Extensive, asymmetric footwall flowstone at a major fault relay with a dry hanging wall was also observed in Level 5 (fig. 18).

Observations of the nearly vertical Elk fault vein were sparse, but where it is exposed, it appears to be very different in character compared to the subparallel Standard fault vein. Although the surface trace of the Elk is mapped as a continuous feature, in several places the continuity of structure is broken by steps or segmentation (figs. 6 and 7). No suitable piercing points were found along the Elk to estimate net displacement, but in its central region it is intraformational because no other formations are exposed in its hanging wall. It also appears to tip out at its northeastern end. Qualitatively, little fault-related damage was seen on either side of the structure; however, the fault vein itself is jointed. The Elk fault-vein core is exposed at one of the main shafts west of the Level 4 tunnel of the Standard Mine, and at this location the core of the Elk fault vein is 32 cm wide and composed of massive to vuggy, coarse-grained, and largely unweathered pyrite (fig. 19). The hanging wall side of the fault-vein core is composed of a deformed mass of galena; the shear sense is compatible with normal, top down to the southeast motion. This mass of pyrite clearly intersects the ground surface; however, no such intersections of the Standard fault vein were exposed. There are other minor faults and fault veins in upper Elk Basin; however, little evidence was found for the existence of many of the faults inferred from lineament analysis or mapped by Gaskill and others (1967).

Veins

Numerous quartz and polymetallic quartz veins are exposed in the upper Elk Basin that are not shown on published maps. Some of these veins are associated with minor normal faults where in every case the vein margins show evidence for motion manifested by polished and lineated striations of the surfaces (fig. 19). Exposed trace lengths range from about 2 m to more than 200 m (fig. 7). These larger veins appear to occur primarily in Ohio Creek but less so in Wasatch within the cirque. Although they are not completely exposed, at several exposures the tips or ends of the veins can be observed, and thus these features are discontinuous. Many of these veins are jointed.

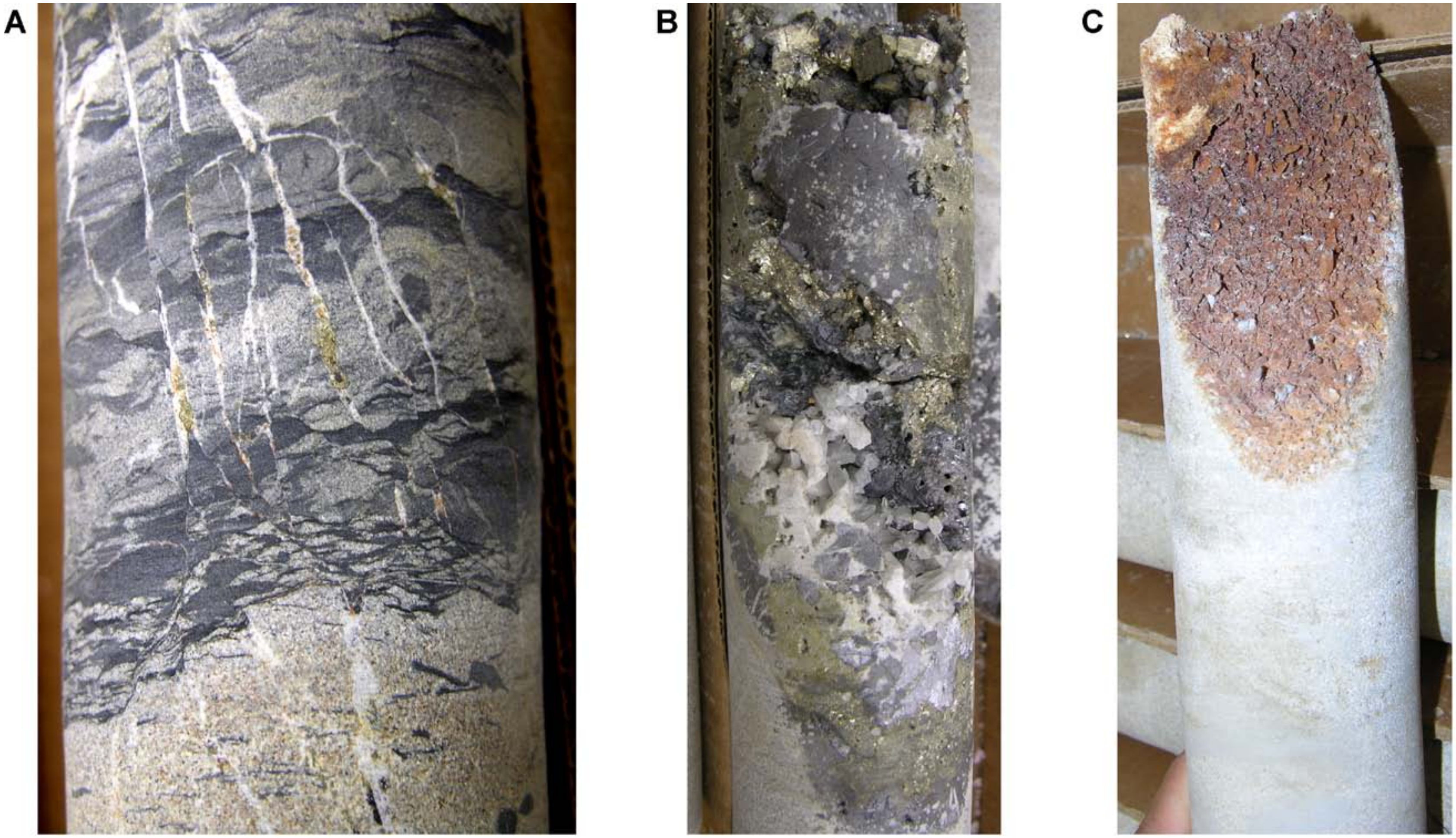


Figure 17. Photographs of drill core from borehole B8, just below Portal 2 of the Standard Mine, in the Ohio Creek Member of Mesaverde Formation footwall damage zone of the Standard fault vein. Each core is approximately 2 in. in diameter. (*A*) 76 ft, small quartz + pyrite fault veins; (*B*) 114 ft, vuggy quartz + pyrite + galena + sphalerite vein; (*C*) 170 ft, iron oxide stain on euhedral quartz vein.

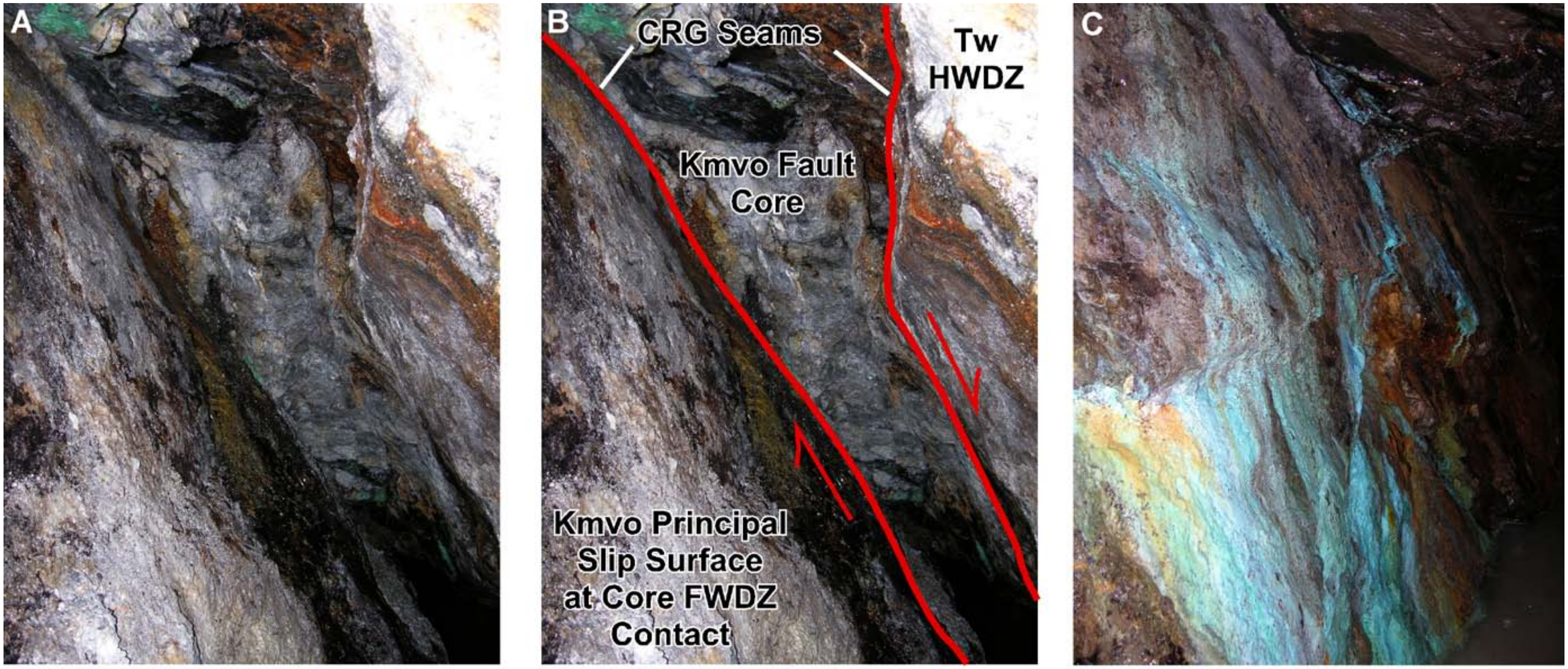


Figure 18. Photographs of the Standard fault vein from Levels 3 and 5 in the Standard Mine. (*A*) View of the Ohio Creek Member of Mesaverde Formation (Kmvo) footwall principal slip surface, Ohio Creek fault core, and Wasatch Formation (Tw) hanging wall in Level 3. The fault core is up to 60 cm wide here. (*B*) Annotated version of figure 18*A*. (*C*) Asymmetric groundwater flow and probable copper-rich precipitate on the Ohio Creek footwall principal slip surface of the Standard fault vein in Level 3.

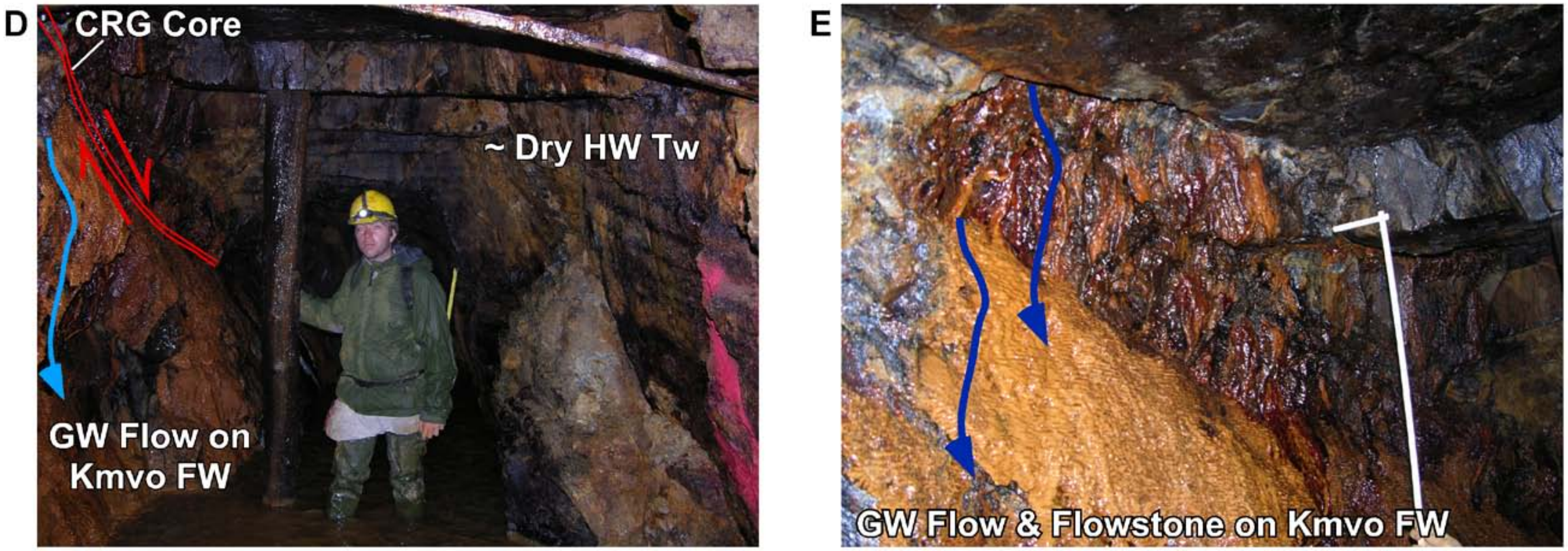


Figure 18.—Continued Photographs of the Standard fault vein from Levels 3 and 5 in the Standard Mine. (*D*) Asymmetric groundwater flow on the Ohio Creek footwall principal slip surface of the Standard fault vein in Level 5. Note the Wasatch hanging wall is nearly dry. (*E*) Detail view of groundwater flowing (blue arrows) on the tripe-like (orange-beige to ochre) and drapestone-like (blood-red) flowstone types on the Ohio Creek footwall principal slip surface of the Standard fault vein in Level 3. CRG, clay-rich gouge; HW, hanging wall; HWDZ, hanging wall damage zone; FW, footwall; FWDZ, footwall damage zone; GW, groundwater.

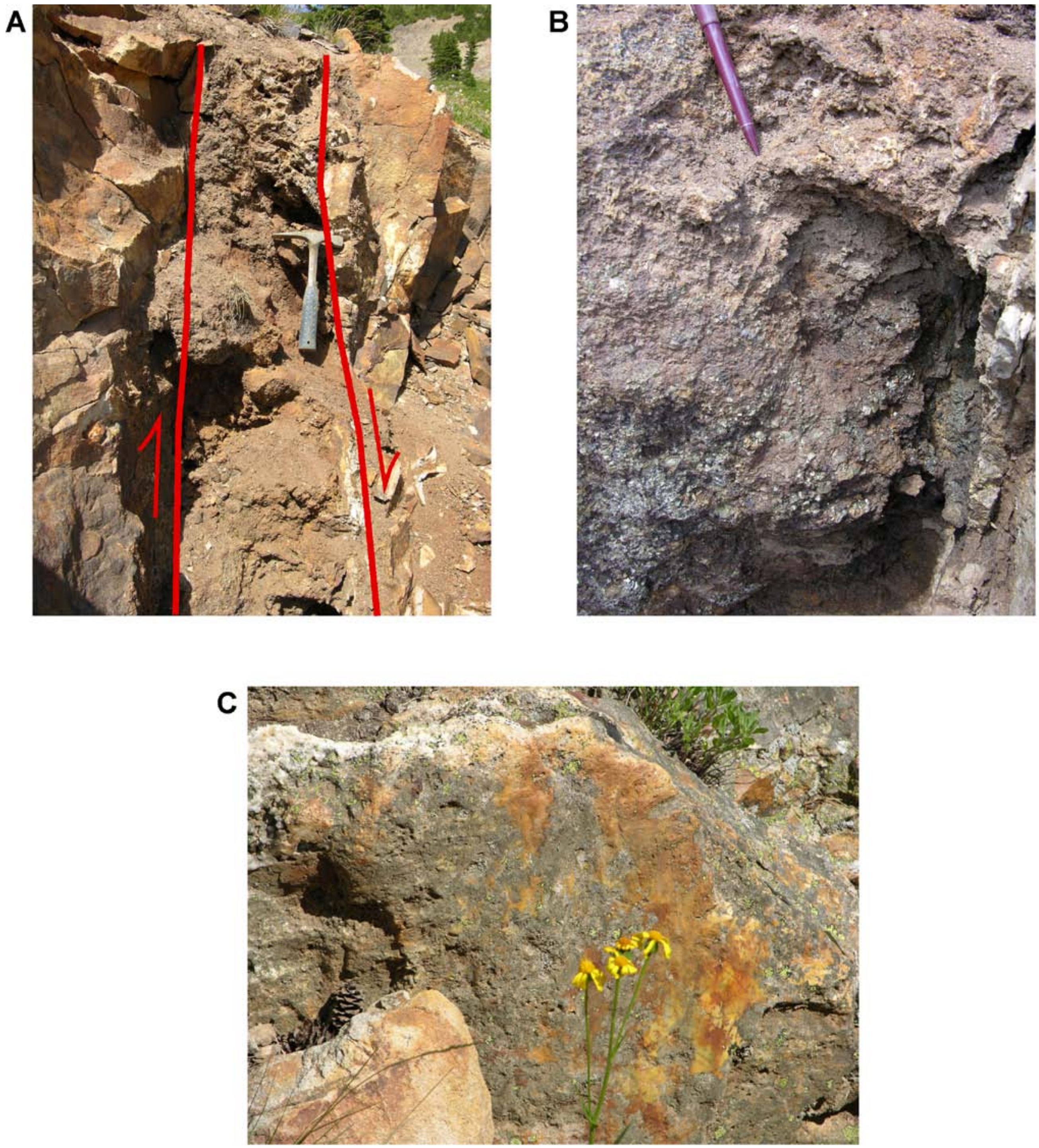


Figure 19. Photographs of the Elk fault vein and a bounding polished slip surface on a fault vein composed of quartz. (*A*) Annotated view of the Elk fault vein looking northeast. (*B*) Detail of the core of the Elk fault vein showing massive pyrite core, vugs, and hanging wall marginal galena with normal shear sense. (*C*) Polished and striated principal slip surface of a quartz fault vein. Note the near-vertical striations on the surface to the right of the flowers.

Macroscopic quartz veins are curviplanar and their widths pinch and swell as indicated by measurements at numerous locations (fig. 10). They range from 3 to 210 cm wide with a median of 33 cm for 15 measurements. The veins are generally complex and mutually crosscutting stockworks of vuggy quartz veins with an occasional master vein that is massive, particularly near the tips of the Standard and Elk fault veins. However, the margins of these veins are discrete and the quartz does not appear to have infused very far into the host rock. Several macroscopic veins have decimeter-scale clots of pyrite, galena, and sphalerite heterogeneously distributed within large vugs. Some sulfide-rich vugs still show significant open space and evidence for brecciation and reaction rim development after deformation. At the watershed scale, three major sets of nearly vertical veins are evident: one trends northeast and is subparallel to the Standard and Elk structures, one trends east-southeast, and one trends north-northwest (fig. 7). In aggregate the vein systems have variable orientations with a mean of 223/90 (fig. 9).

Summary of Key Observations and Hypotheses

1. The Standard and Elk structures are fault veins. They likely form discrete and distinctive mechanical and hydrologic heterogeneities that cut the otherwise subhorizontal and jointed Upper Cretaceous Ohio Creek Member of Mesaverde Formation and Tertiary Wasatch Formations.
2. The Wasatch Formation has been juxtaposed against the Ohio Creek Member by up to approximately 90 m of top down to the southeast normal displacement with a minor component of left-lateral motion along the Standard fault. The Elk fault vein shows no suitable piercing points to estimate its net displacement but it appears to tip out at its northeastern end.
3. The Standard fault vein is composed of a complex, pinching and swelling, massive to stockwork, polymetallic quartz vein network that is cut by a brittle fault on its southeast (or hanging wall) side. A few observations indicate that the vein formed before its neighboring fault:
    - The margins of the quartz vein, where it is massive, have polished and striated slip surfaces indicating that the quartz was solid at the time of slip.
    - Deformed quartz veins are entrained in the fault core indicating that the vein was present before the fault core developed.
    - An apparent argillic alteration halo around the master vein network may have formed asymmetrically in the hanging wall of the vein, restricted to the Ohio Creek; subsequently it was deformed in the fault core, which may indicate that the vein caused thermal and mineralogical weakening and that localization of strain along the evolving Standard fault subsequently occurred.
4. The Standard fault vein appears to have a poorly developed but complex damage zone composed of polymetallic quartz veins, some open fractures, vugs, breccia zones, small faults, and some minor slip surfaces. Some very small faults in the Ohio Creek FWDZ are filled with polymetallic quartz veins, possibly indicating syntectonic hybrid opening and shearing-mode deformation. Other structures in the FWDZ observed in drill core include heterogeneously distributed open and leached quartz veins, vugs with unoxidized and in other places oxidized metallic phases, and some evidence of uncemented breccias. Although small fault and fault-related joint intensity between the Elk and Standard fault veins were not observed to be extensive, this could be an important location to determine if there is such damage at higher intensities compared with that on the northwest side of the Elk (footwall protolith) and southeast side of the Standard (hanging wall protolith) in this paired fault vein system.
5. A well-developed, complex, pyritiferous, and nearly continuous clay-rich fault core appears to involve exclusively the entrainment and deformation of mineralized, argillically altered, and quartz-veined Ohio Creek Member. This core is a single seam of clay in some localities but in others it is a lens-like zone of deformed Ohio Creek between two seams of clay-rich gouge that enclose the lens along its outer contacts with the damage zone on either side.
6. In spite of very thin surficial deposits, very few direct observations of the characteristics of the Standard faults' intersection with the ground surface were made. However, it can be inferred that the fault-vein architecture is similar to that observed in the mine and where other polymetallic fault veins intersect the ground surface. Where the fault veins are complex networks of quartz or polymetallic veins within a few meters of their neighboring fault zones, their bulk permeability may be relatively low in contrast to the pervasively jointed host rocks. However, cross-cutting and open joints in the fault veins may cause them to be similar in bulk permeability to the host rocks with discrete variations in permeability due to the joint networks.
7. Localized vuggy and brecciated zones within the fault veins and the FWDZ of the Standard fault vein that intersect the ground surface, although likely not extensive, may be discrete pathways for surface water infiltration, reaction of oxygenated waters with sulfides, and shallow groundwater flow around and into the mine. However, the damage zone on either side of the fault core in general appears to be poorly developed such that a large bulk permeability contrast between the damage zone and the host rocks is not expected. This observation suggests that the damage zone does not consistently act as a major conduit for the flow of shallow groundwater downward to the mine workings. The high clay content of the fault core suggests that it also does

not act as a major conduit for groundwater flow. At this time these statements are hypotheses; however, there are a number of ways to test these hypotheses that are beyond the scope of the current study.

8. Localized and highly concentrated polymetallic sulfide vein mineral deposition associated with the Standard and Elk fault veins, in contrast to pervasive and disseminated pyrite deposition in the surrounding host rocks, is likely the primary source of metal contamination in waters that drain the Standard Mine workings. Although there has been extensive sulfide mineral leaching, much of the sulfide mineralization, particularly in vuggy open space, is in many places unoxidized, which suggests the presence of an abundant supply of source metals in the system yet to be oxidized.
9. Other polymetallic-to-barren quartz veins exist throughout the upper basin. Many of these are discontinuous in length and, although some are jointed, they may have relatively low to similar bulk permeability compared with the sedimentary host rocks they cut and thus may act as localized baffles to subsurface groundwater flow.
10. All observed rocks, except the clay-rich gouge in the Standard Mine, are cut by a pervasive, presumably iron-oxide stained, heterogeneously distributed, open network of vertical and subhorizontal joints.
11. Borehole televiewer logs show evidence (consistent with outcrop observations and measurements) of a near-surface, heterogeneous layer of highly fractured sedimentary bedrock, particularly in the Ohio Creek Member. Many subhorizontal but highly curviplanar fractures have formed along preexisting bedding-related features such as small crossbed sets, that may have opened preferentially in response to unloading after glaciation. This layer of variable thickness, joint intensity, and other fracture network properties transected by near vertical joints may be an important control on surface water infiltration and vadose zone processes.
12. Discrete and asymmetric groundwater flow was observed throughout Levels 3 and 5 in the Standard Mine. This flow was in the form of point emanations and sheets. It emanated primarily from the Ohio Creek footwall side of the Standard fault vein and on the footwall side of the nearly continuous seam of clay-rich fault gouge marking the contact between the footwall damage zone and fault core. Adjacent to many of these flow zones, the Wasatch hanging wall was dry (possible seasonal variations of this flow asymmetry are unknown). This suggests that the Standard fault vein is a partial barrier to flow across the fault but may locally behave as an asymmetric, discrete conduit along the fault at depth possibly controlled by what appears to be a poorly developed damage zone. Once within the workings, water freely flows from higher to lower levels via raises and stopes to ultimately discharge at the various mine portals.
13. Most flow zones were also marked by an unidentified flowstone precipitate. This suggests these flow zones are long-lived.
14. Low grade but pervasive hydrothermal alteration marked by disseminated pyrite in the Ohio Creek and Wasatch occurred. Other than containing pyrite, this alteration is weakly argillic in Ohio Creek and weakly propylitic in Wasatch, suggesting that primary composition played an important role in the resulting alteration mineral assemblages. Other than the discrete quartz veins, no evidence for silicification was observed in outcrop or in thin sections.
15. Preferential leaching of disseminated pyrite occurred in all surface exposures of the poorly indurated Upper Cretaceous Ohio Creek Member except where vuggy polymetallic quartz veins cut it. However, the well-indurated Tertiary Wasatch Formation showed abundant fresh pyrite in surface exposures. This is consistent with the intergranular permeability of Ohio Creek being greater than that of the Wasatch very near the surface.
16. Mercury injection capillary pressure data indicates the intergranular porosity and permeability of Ohio Creek is about an order of magnitude greater than the clay-rich gouge of the Standard fault. The intergranular porosity and permeability of the Wasatch Formation are several orders of magnitude lower than porosity and permeability of the Ohio Creek or clay-rich gouge.
17. Although we did not conduct any hydraulic aquifer testing to sample large aquifer volumes which would include the hydraulic properties of macroscopic fracture networks in the Ohio Creek and Wasatch, test results would likely result in bulk permeability values that are orders of magnitude greater than the MICP intergranular permeabilities reported. The basis for this statement is from commonly reported hydraulic test data from similar rocks, observations of flow emanating directly from fractures in the mine, and from numerical modeling of fracture network permeabilities (for example Caine and Tomusiak, 2003). However, the bulk permeability of Ohio Creek may be higher than that of Wasatch based on flow in the mine apparently emanating predominantly from the Ohio Creek footwall, Ohio Creek being leached of pyrite in the near surface compared with Wasatch, and outcrop observations suggesting many fewer subhorizontal joints in Wasatch.
18. Estimation of the ground surface elevation gradient field derived from the 30 m National Elevation Database Digital Elevation Model for Elk Basin suggests that surface water and near-surface groundwater within and under sparse surficial deposits may be channeled between the Elk and Standard fault veins. This potential near-surface “flow” on the Ohio Creek footwall side of the Standard fault vein is parallel to the surface fault trace and is directed towards and at a high angle to the trace on the Wasatch hanging wall side. A large propor-

tion of this potential near-surface "flow" comes from the Wasatch hanging wall side of the Standard fault vein. Although the ground surface gradient does not reflect the subsurface hydraulic gradient in the saturated zone, which is essentially undefined in Elk Basin, it may be a good approximation of it for very shallow groundwater within and immediately below surficial deposits and soils. With increasing depth in the saturated zone, the effects of near-surface topography likely have a decreasing effect and one might imagine that the deeper groundwater flow system has an overall southerly flow direction influenced by Scarp Ridge and the flanking ridges of the Elk Basin cirque. If this is true, it suggests that the near-surface and deeper groundwater flow directions may be different; it may explain the asymmetric flow of groundwater observed in the mine workings, and implies that flow into the mine workings may be largely from deeper groundwater rather than near-surface waters that infiltrate and flow directly downward through the fault vein.

The key observations, data, and hypotheses lead to a conceptual model as follows and as depicted in figure 20:

- The Standard and possibly the Elk fault veins are the primary sources of metal solutes in the surface and groundwater flow systems.

- The intergranular porosity and permeability of the sedimentary host rocks is likely relatively low compared with the heterogeneously distributed but apparently relatively high-permeability, iron-oxide stained joint networks. These joint networks have high intensity near the surface, which variably decreases with depth and as such are likely a major control on infiltration

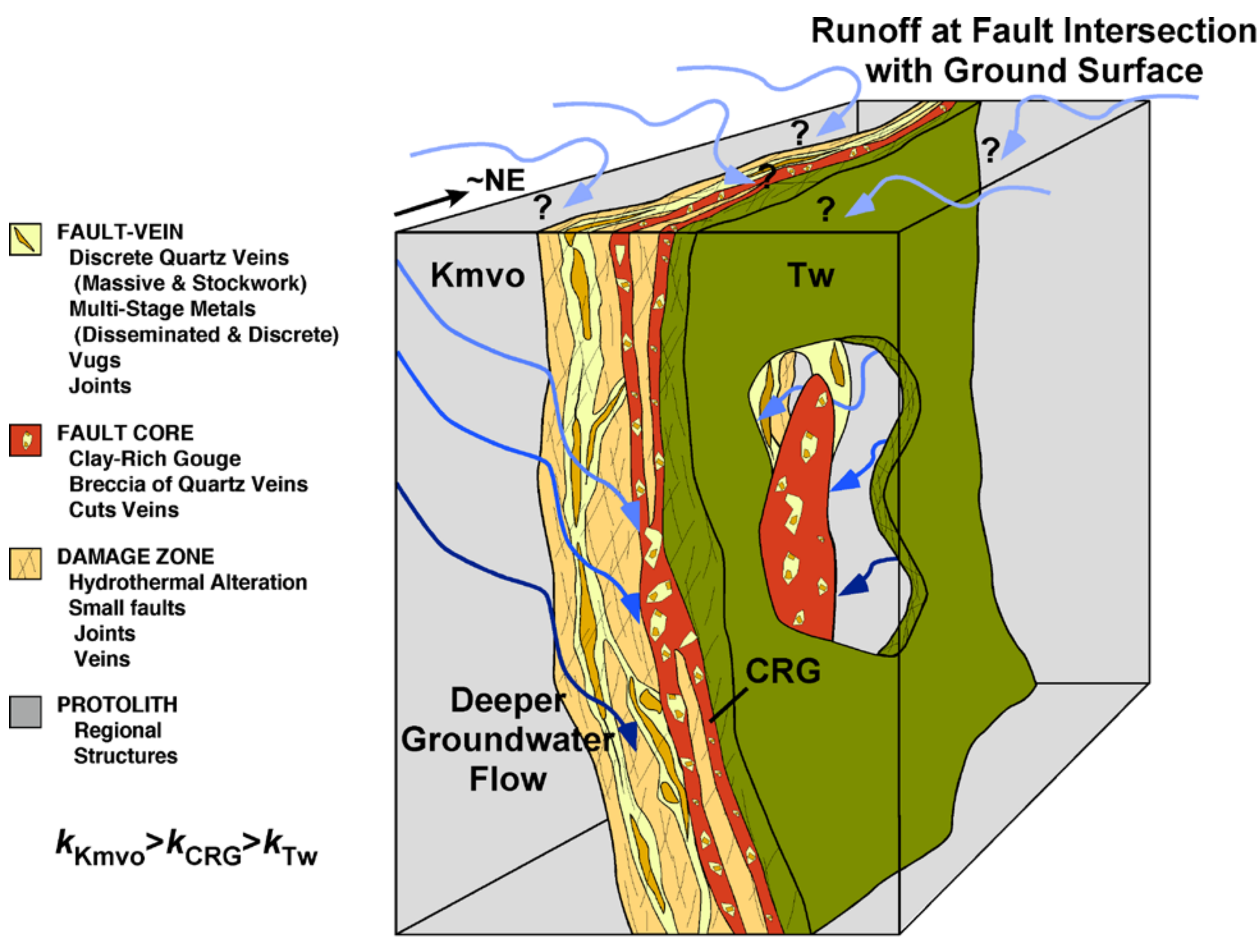


Figure 20. Conceptual diagram for the architecture and permeability structure of the Standard fault vein and its possible interactions with surface and groundwaters. Each architectural component of the fault vein is shown and the fractured protolith is removed. The fault juxtaposition of Wasatch Formation on Ohio Creek Member is shown with a cutout through the Wasatch hanging wall. The cutout illustrates the heterogeneity and three dimensionality of the fault vein and its possible behavior as a combined conduit-barrier impeding deeper groundwater flow from the footwall through the fault into the hanging wall but allowing downflow or lateral flow along the fault. The curved blue arrows depict the possible tortuous flow paths and possible decoupling of oxygenated surface waters (light blue) from less oxygenated groundwaters (darker shades of blue). Kmvo = Upper Cretaceous Ohio Creek Member of Mesaverde Formation, Tw = Tertiary Wasatch Formation, CRG = clay-rich gouge, k = bulk permeability, NE = northeast.

and groundwater flow in the subsurface. These heterogeneities may also cause tortuous flow paths and possible decoupling of oxygenated surface waters from less oxygenated groundwaters (fig. 20).

- The juxtaposition of possibly lower porosity and permeability Tertiary Wasatch Formation against the Upper Cretaceous Ohio Creek Member of Mesaverde Formation along the Standard fault vein, in combination with relatively low permeability (albeit heterogeneous) polymetallic quartz vein networks and clay-rich fault gouge in the core of the fault, likely controls the storage and flow of groundwater in the vicinity of the fault vein and to the mine workings.
- Given the character of joint networks, fault-related rocks, sedimentary juxtaposition, and the potential variation in surface versus subsurface hydraulic gradients relative to the orientation of the Standard fault vein, the structure may not be a major conduit for direct groundwater flow from the near-ground surface downward to the mine workings.

The Standard fault vein appears to be a complex, asymmetric, combined conduit-barrier to groundwater flow. Groundwater within the Ohio Creek that intersects the fault core and the juxtaposed Wasatch is likely impeded from crossing the fault vein; groundwater may instead flow along it, and possibly laterally within it, before discharging into the mine. These observations and the potentially different surface water versus likely deeper groundwater gradients may indicate that the dominant source of groundwater entering the mine workings is deeper groundwater flow, potentially transported rapidly through joint networks from the greater volume of the sedimentary bedrock in the upper Elk Basin.

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