

Sufco

FINAL REPORT

EVALUATION OF THE FACTORS
CONTRIBUTING TO THE TDS IN
SUFCO'S MINE DISCHARGE WATER

November 20, 1993

MAYO AND ASSOCIATES

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Mine Discharge Water

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Evaluation of the Factors Contributing to the TDS in SUFCO's
Mine Discharge Water

BACKGROUND AND PURPOSE

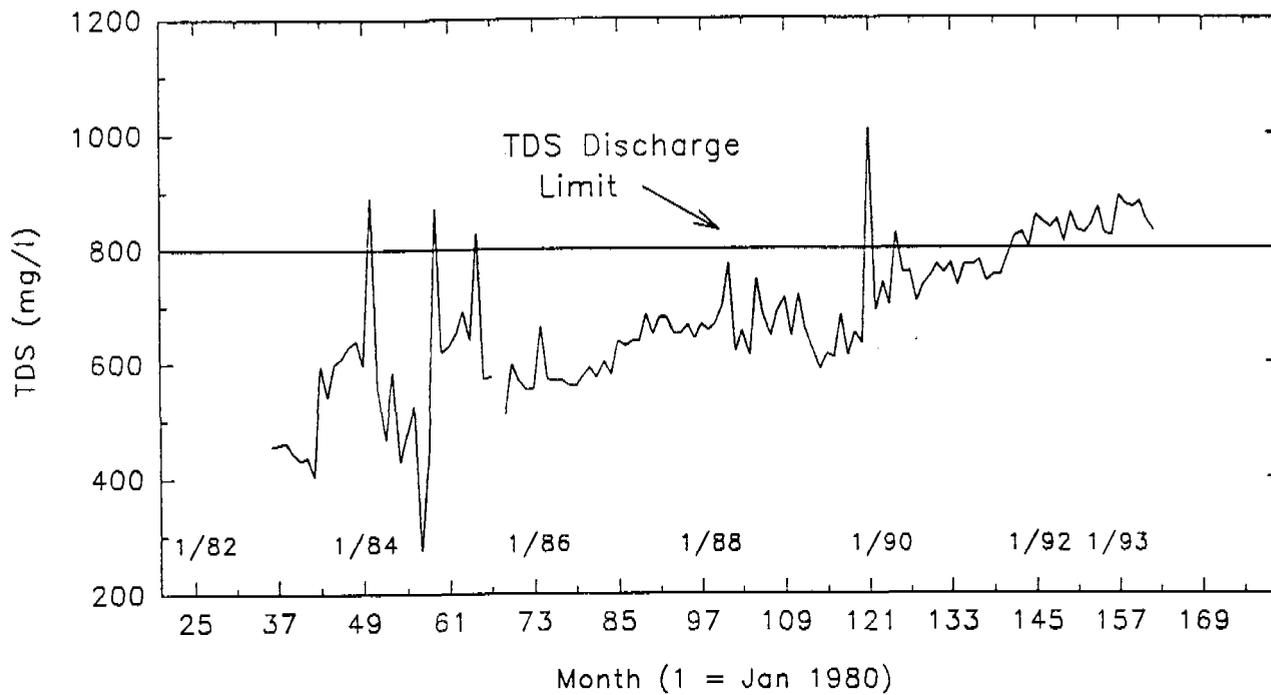
The total dissolved solids (TDS) of the discharge water from the SUFCO Mine (PT003) has been increasing since early-1990 (Figure 1). Between January 1990 (month 121) and July 1993 (month 162), the mean TDS increased from about 650 mg/l to about 850 mg/l. Since mid-1991 the discharge has exceeded SUFCO's Utah Pollution Discharge Elimination System (UPDES) TDS limit of 800 mg/l.

The purpose of this investigation is to determine the factors responsible for the elevated TDS.

METHODS OF INVESTIGATION

Historical mine water quality and discharge data were obtained from SUFCO. Results of an early 1993 water quality sampling program performed by SUFCO personnel were evaluated. Approximately 50 roof drips and floor waters were sampled as part of this initial investigation. Because most of the water quality data had large cation-anion balance errors, this data set was not

Figure 1 TDS hydrograph of SUFCO mine discharge from discharge point PT003.



(TDSQ2.sp5)

useful for quantitative evaluation. The source of the cation-anion balance errors was subsequently investigated by Mayo and Associates and the problem has been resolved (Appendix A).

A preliminary analysis of the existing data suggested that the elevated TDS of the mine discharge water was due to elevated TDS, particularly SO_4^{2-} , of the roof drip water in the new portion of the mine. This new mining area is located east of the surface feature Quitchupah Creek. Based on preliminary analysis of the existing data a plan of investigation was designed and implemented. The plan consisted of the following elements:

1. The collection of water quality samples from roof drips and floor waters at selected locations in the mine and at the mine discharge point PT003. Samples were collected on April 12 and 13, 1993. Samples were analyzed in the field for pH and temperature. Major ions and TDS concentrations were determined by Mountain States Analytical Laboratory in Salt Lake City, Utah. Stable isotopic analysis for $\delta^2\text{H}$, $\delta^{18}\text{O}$, $\delta^{13}\text{C}$, and $\delta^{34}\text{S}$ were performed by Geochron Laboratories in Cambridge, Massachusetts. A few roof samples were also analyzed for the unstable isotopes ^3H and ^{14}C by Geochron Laboratories.

Water samples were collected and analyzed following U.S.E.P.A. (1981) procedures. Solute data were plotted on a trilinear (Piper, 1944) diagram for visual inspection. Saturation indices were calculated with the computer code WATEQF (Plummer and others, 1976). Isotopic samples for $\delta^2\text{H}$, $\delta^{18}\text{O}$, and ^3H were collected and preserved in sealed glass bottles. Isotopic samples for $\delta^{13}\text{C}$, $\delta^{34}\text{S}$, and ^{14}C were precipitated with BaCl_2 .

2. A floor-water budget for the sampling period was developed by SUFCO personnel.
3. The geochemical and other data were analyzed by graphical, statistical and computer methods to:
 - a. characterize mine hydrogeology,
 - b. determine mass contributions of TDS of each potential source, and
 - c. evaluate the potential for TDS changes in future mine discharge waters.

OVERVIEW OF MINE OPERATIONS

Prior to 1985 mining operations only used continuous mining machines. These machines created the traditional room and pillar mine openings. The continuous mining machine makes openings similar to tunnels, called rooms, and the pillars are walls separating the rooms. Longwall mining requires prior development by continuous mining machines parallel to the direction of longwall mining along the entire length of the area to be longwall mined. In October 1985 SUFCO added a longwall mining machine to the existing inventory of continuous mining machines. Longwall mining has been conducted in three separate regions of the mine, herein designated as Longwall Areas 1, 2 and 3 (Figure 2). A brief history of each area follows:

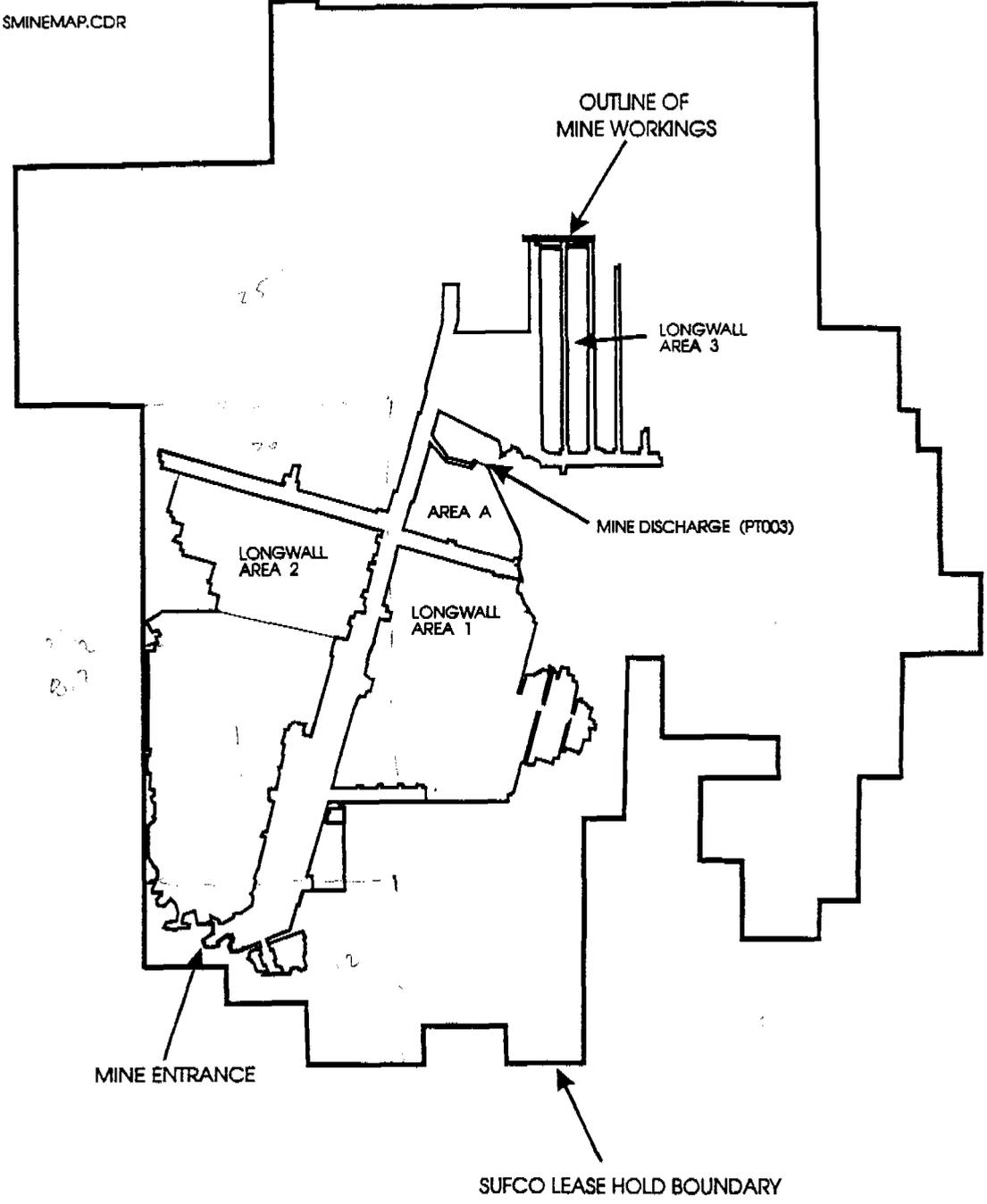
Area 1 - mined from October 1985 to December 1989,

Area 2 - mined from January 1990 to January 1992, and

Area 3 - mined from February 1992; mining continues to date. Initial development for longwall mining began in December 1990.

Although the average height of the coal seam is 13.5 feet, the average height of mine openings is 9 feet. Coal is left in the floor and ceiling of mine openings to increase roof stability and ensure that foreign material does not mix with the mined coal.

Figure 2 Map showing the location of mine workings relative to the SUFCO lease area. Longwall Areas 1, 2, and 3, and Area A are described in the text.



The gentle regional dip of the bedrock results in mine tunnels and longwall openings that are nearly horizontal.

Coal is removed from the mine by means of a conveyer belt. Some mine water is used to suppress coal dust on the conveyer belt and in the truck loading area located outside the mine.

Continuous miners and the longwall miner create openings with fundamentally different structural properties. Continuous miners bore tunnels averaging 9 feet tall and 18 feet wide. Blocks of unmined coal (pillars) are left between individual tunnels. With appropriate shoring of weak sections these tunnels can remain open indefinitely. Old mined areas are either used as transportation and ventilation routes or are sealed where they connect with open tunnels used in mining operations.

Longwall mining creates openings 7 to 13 feet tall and up to 750 feet wide. The roof of the longwall mined area is unstable and collapses within hours to days after being mined. The net effect of longwall mining is to create a large rubble zone.

Until June 1993, all exposed mine floor, wall, and roof areas were dusted with gypsum rock dust ($\text{CaSO}_4 \cdot x\text{H}_2\text{O}$) to retard fire and prevent explosions. In July 1993 magnesium limestone $\text{Mg}_x\text{Ca}_x(\text{CO}_3)_2$ was substituted for gypsum. Dusting is a continuous

process in the open mine area. New areas are immediately dusted, and previously dusted areas are redusted as needed to decrease the bulk combustible content and replace dust lost to flowing mine waters.

The movement of water in the mine is managed by a system of collecting (sumps) and pumping stations, pipes, and free flow along the mine floor. The system is periodically modified as new mining proceeds.

The longwall mining machine uses hydraulically operated longwall shields to support the roof during mining. Longwall shields are powered by emulsion fluid consisting of 95% water and 5% soluble oil. Until a fugitive emulsion collection systems was install in June 1992 and became fully operational in August 1992, some emulsion fluid discharged into Longwall areas 1 and 2. The exact amount of fugitive fluid is hard to determine because it depends on the number of valves by-passing and the frequency of changes in mining heights. Only minimal amounts of emulsion currently leak from the longwall mining machine.

The emulsion is organic-based containing substantial amounts of sulfate (SO_4^{2-}), sodium (Na^+), and other inorganic ions. The exact composition of the emulsion used in Longwall Areas 1 and 2 is

unknown. The inorganic content of currently used emulsion is listed in Appendix B.

Mining operations sometimes result in local low spots in the floor of the mine. In areas where water flows on the mine floor, these low spots become small ponds. Crushed carbonate rock is used to fill the ponded areas.

GEOLOGIC AND HYDROGEOLOGIC SETTING

Geology

The SUFCO mine is located approximately 30 miles east of Salina, Utah, in the High Plateaus Section of the Colorado Plateau Physiographic Province. The mine property encompasses approximately 17,000 acres. The surface topography consists of a rolling upland plateau that is deeply dissected by two major tributaries of Quitchupah Creek. The northwest trending North Fork of Quitchupah Creek bisects the mine property in half, and the west trending Convulsion Canyon forms the southern boundary of the mine property (Figure 3). The confluence of the two tributaries lies south of the mine property. Surface elevation of the plateau ranges from about 8,400 to 8,500 feet. Duncan Mountain and Big Ridge rise to about 9,200 feet along the western

Table 1 Chemical and isotopic analyses of roof drip, floor water, and the mine discharge water taken during the April 12 and 13, 1993 sampling period.

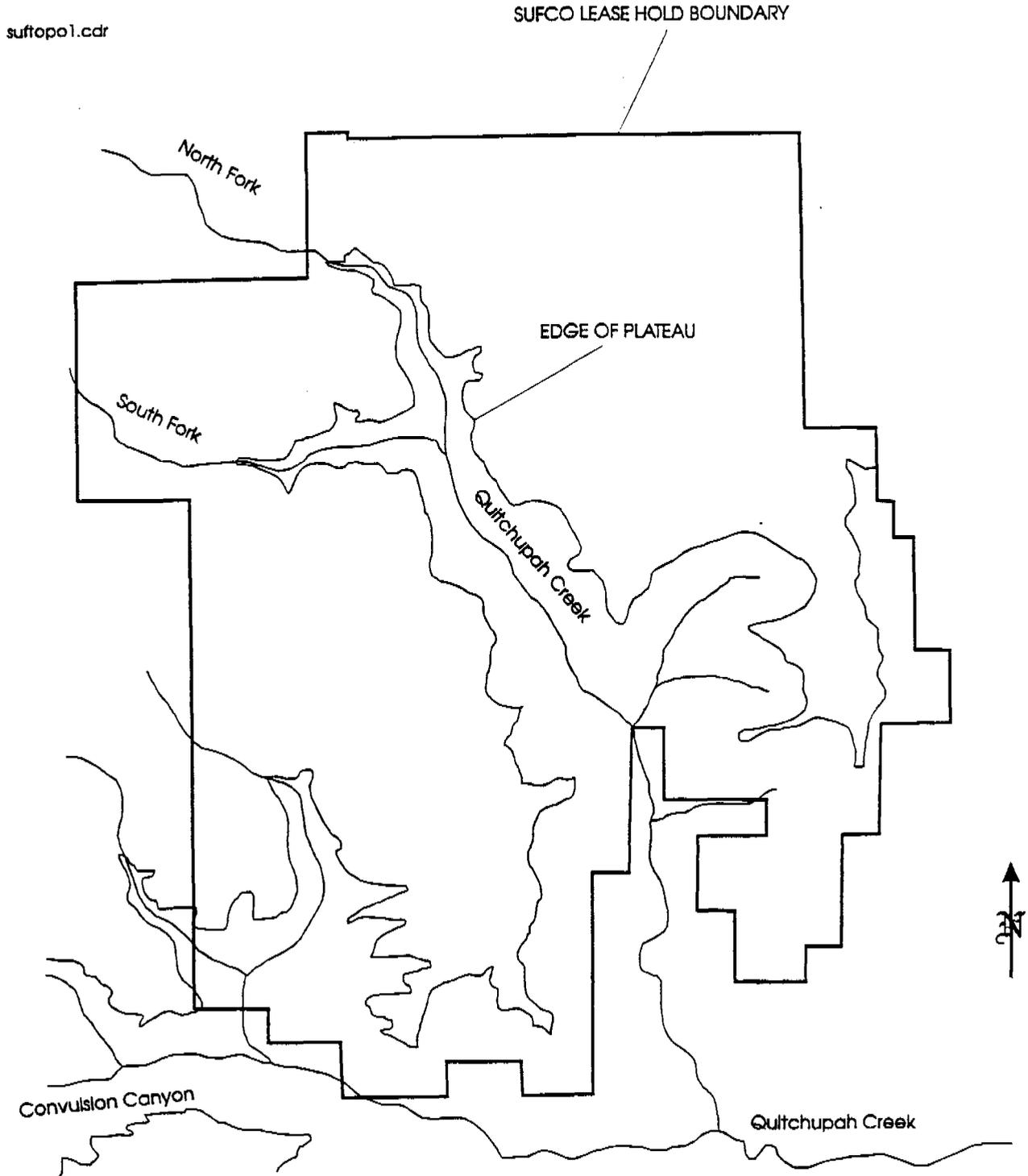
| Sample # | Location | T | pH | TDS* | TDS | ----- meq/l ----- | | | | | | ----- o/oo ----- | | | | TU | pmc | |
|----------------------------|----------|------|------|------|-------|-------------------|------|------|------|------|------|------------------|-------|--------|-------|------|-----------|-----------|
| | | | | mg/l | meq/l | Ca | Mg | Na | K | HCO3 | SO4 | Cl | 18O | 2H | 13C | 34S | 3H | 14C |
| Roof Drips Longwall Area 3 | | | | | | | | | | | | | | | | | | |
| R1 | 4efacerd | | 7.95 | 460 | 16.96 | 3.50 | 4.20 | 0.72 | 0.11 | 5.46 | 2.46 | 0.51 | -16.4 | -122 | -10.1 | 19.3 | | |
| R2 | rebuild | 11.5 | 7.60 | 700 | 25.77 | 6.85 | 5.41 | 0.62 | 0.10 | 8.17 | 3.98 | 0.64 | -16.4 | -123 | -5.6 | 8.9 | <3.0 | 7.2 ± 1.2 |
| R3 | 8L4EC34R | | 7.40 | 570 | 20.00 | 5.00 | 4.30 | 0.60 | 0.10 | 6.20 | 3.30 | 0.50 | -16.5 | -127 | -7.5 | 10.7 | | |
| R4 | WMRD | 11.0 | 7.25 | 500 | 17.40 | 4.40 | 3.60 | 0.60 | 0.10 | 5.50 | 2.80 | 0.40 | -16.6 | -128 | -7.7 | 11.6 | | |
| R5 | nmfc210 | | 7.65 | 480 | 17.64 | 4.42 | 3.57 | 0.71 | 0.06 | 5.86 | 2.56 | 0.46 | -17.3 | -128 | -12.1 | 13.6 | 1.1 ± 2.4 | |
| R6 | quitchrd | | 7.95 | 570 | 21.62 | 5.23 | 4.97 | 0.52 | 0.05 | 6.61 | 3.14 | 1.10 | -17.2 | -129 | -6.6 | 8.0 | | |
| mean | | 11.3 | 7.63 | 547 | 19.90 | 4.90 | 4.34 | 0.63 | 0.09 | 6.30 | 3.04 | 0.60 | -16.7 | -126 | -8.3 | 12.0 | | |
| std | | | 0.26 | 80 | 3.09 | 1.03 | 0.67 | 0.07 | 0.02 | 0.93 | 0.51 | 0.23 | 0.4 | 3 | 2.2 | 3.7 | | |
| Roof Drips Longwall Area 2 | | | | | | | | | | | | | | | | | | |
| R7 | 3WC62rd | 14.0 | 7.65 | 290 | 10.40 | 2.70 | 1.90 | 0.50 | 0.00 | 4.30 | 0.70 | 0.30 | -17.5 | -130 | -9.9 | 12.7 | | |
| R8 | 3WC44rd | 13.0 | 7.60 | 290 | 10.40 | 2.70 | 1.80 | 0.50 | 0.00 | 4.40 | 0.70 | 0.30 | --- | --- | --- | --- | 1.1 ± 2.4 | |
| R9 | 3WC16rd | | 7.55 | 330 | 10.80 | 3.10 | 2.00 | 0.30 | 0.00 | 4.40 | 0.70 | 0.30 | -17.4 | -132 | -9.6 | 15.9 | | |
| mean | | 13.5 | 7.6 | 303 | 10.53 | 2.83 | 1.90 | 0.43 | 0.00 | 4.37 | 0.70 | 0.30 | -17.5 | -131.0 | -9.8 | 14.3 | | |
| std | | | 0.0 | 19 | 0.19 | 0.19 | 0.08 | 0.09 | 0.00 | 0.05 | 0.00 | 0.00 | | | | | | |
| Roof Drips Longwall Area 1 | | | | | | | | | | | | | | | | | | |
| R10 | PT062rd | 10.0 | 7.65 | 370 | 14.60 | 4.40 | 2.50 | 0.30 | 0.00 | 6.00 | 1.10 | 0.30 | --- | --- | --- | --- | | |
| R11 | 3ec8 | | 7.25 | 380 | 14.59 | 4.20 | 2.71 | 0.38 | 0.04 | 5.62 | 1.33 | 0.31 | -17.5 | -127 | -10.1 | 8.2 | | |
| R12 | rmc128 | | 8.05 | 400 | 15.23 | 4.36 | 2.84 | 0.32 | 0.03 | 6.02 | 1.33 | 0.33 | -17.2 | -125 | -7.7 | 11.4 | 3.3 ± 2.4 | |
| R13 | 2ec41rd | | 7.90 | 430 | 17.42 | 3.45 | 4.71 | 0.37 | 0.08 | 6.37 | 1.37 | 1.07 | -16.9 | -123 | -11.2 | 9.3 | | |
| mean | | 10.0 | 7.7 | 395 | 15.46 | 4.10 | 3.19 | 0.34 | 0.04 | 6.00 | 1.28 | 0.50 | -17.2 | -125.0 | -9.7 | 9.6 | | |
| std | | | 0.3 | 23 | 1.16 | 0.38 | 0.89 | 0.03 | 0.03 | 0.27 | 0.11 | 0.33 | 0.2 | 1.6 | 1.5 | 1.3 | | |

Table 1 con't

| Sample # | Location | T | TDS* | | meq/l | | | | | | | | o/oo | | | | TU | pmc |
|-----------------------------------|----------|------|------|------|-------|-------|-------|-------|------|-------|-------|------|--------|--------|-------|------|----|-----|
| | | | pH | mg/l | meq/l | Ca | Mg | Na | K | HCO3 | SO4 | Cl | 180 | 2H | 13C | 34S | 3H | 14C |
| Roof Drips Longwall Areas 1 and 2 | | | | | | | | | | | | | | | | | | |
| mean | | 5.75 | 7.66 | 349 | 13.00 | 3.47 | 2.55 | 0.39 | 0.02 | 5.18 | 0.99 | 0.40 | -12.27 | -90.54 | -6.88 | 8.38 | | |
| Floor Waters | | | | | | | | | | | | | | | | | | |
| F1 | 4Efp | | 7.60 | 2620 | 74.40 | 24.20 | 6.70 | 5.20 | 0.10 | 3.00 | 34.50 | 0.70 | -15.0 | -107 | -4.3 | 16.0 | | |
| F2 | 8l4eface | | 7.65 | 1120 | 34.31 | 6.78 | 5.82 | 3.98 | 0.17 | 6.45 | 10.50 | 0.61 | -16.9 | -126 | -7.6 | 13.8 | | |
| F3 | nmface | 11.0 | 7.25 | 2380 | 69.38 | 14.20 | 5.81 | 14.60 | 0.27 | 3.46 | 26.70 | 4.34 | -15.9 | -125 | -6.9 | 16.3 | | |
| F4 | NM4smpwp | 11.0 | 8.00 | 710 | 19.60 | 5.00 | 3.80 | 0.90 | 0.10 | 5.20 | 4.20 | 0.40 | --- | --- | --- | --- | | |
| F5 | NM4smpmw | | 7.50 | 850 | 26.60 | 5.20 | 5.20 | 2.90 | 0.10 | 5.00 | 7.70 | 0.50 | -16.7 | -126 | -9.3 | 8.3 | | |
| F6 | LWBAirpm | 12.0 | 8.10 | 880 | 27.20 | 4.90 | 5.40 | 3.10 | 0.10 | 5.20 | 8.00 | 0.50 | --- | --- | --- | --- | | |
| F7 | nm3sump | 12.0 | 7.80 | 1400 | 42.62 | 9.80 | 7.50 | 3.49 | 0.12 | 4.94 | 16.00 | 0.77 | -16.4 | -122 | -5.4 | 12.2 | | |
| F8 | 6nsump | 15.0 | 8.10 | 770 | 22.60 | 4.02 | 3.99 | 3.15 | 0.10 | 6.65 | 4.33 | 0.36 | -17.2 | -124 | -9.1 | 11.4 | | |
| F9 | 3wsump | 14.0 | 7.75 | 630 | 22.94 | 4.15 | 3.85 | 3.30 | 0.09 | 7.13 | 4.08 | 0.34 | --- | --- | --- | --- | | |
| F10 | 1LNMseal | 15.0 | 7.15 | 790 | 25.80 | 5.20 | 4.40 | 3.10 | 0.10 | 8.20 | 4.20 | 0.60 | -17.3 | -132 | -11.7 | 10.6 | | |
| F11 | 6eseals | | 7.15 | 1170 | 37.39 | 7.85 | 8.15 | 2.48 | 0.14 | 8.99 | 9.35 | 0.43 | -17.2 | -122 | -8.2 | 9.3 | | |
| F12 | 1L6ENS | 15.0 | 7.05 | 1890 | 60.60 | 10.90 | 12.80 | 5.70 | 0.20 | 10.10 | 20.40 | 0.50 | -17.3 | -125 | -8.1 | 6.8 | | |
| mean | | 13.1 | 7.59 | 1268 | 38.62 | 8.52 | 6.12 | 4.33 | 0.13 | 6.19 | 12.50 | 0.84 | -12.5 | -92 | -5.9 | 8.7 | | |
| std | | | 0.36 | 647 | 18.37 | 5.60 | 2.42 | 3.31 | 0.05 | 2.06 | 9.54 | 1.06 | 7.2 | 54 | 3.8 | 5.7 | | |
| Mine Discharge | | | | | | | | | | | | | | | | | | |
| D1 | PT003s | 12.0 | 7.15 | 850 | 27.41 | 5.27 | 4.97 | 3.24 | 0.12 | 5.58 | 7.74 | 0.49 | -17.0 | -130 | -6.1 | 9.9 | | |
| D1 | PT003e | 12.0 | 7.25 | 840 | 25.71 | 5.02 | 4.78 | 3.14 | 0.11 | 5.50 | 6.66 | 0.50 | -16.9 | -128 | -8.2 | 9.9 | | |
| mean | | 12.0 | 7.20 | 845 | 26.56 | 5.15 | 4.88 | 3.19 | 0.11 | 5.54 | 7.20 | 0.50 | -17.0 | -129 | -7.1 | 9.9 | | |
| std | | 0.0 | 0.05 | 5 | 0.85 | 0.13 | 0.10 | 0.05 | 0.00 | 0.04 | 0.54 | 0.00 | 0.0 | 1 | 1.1 | | | |

* TDS of sample R2 has been assigned a content of 700 mg/l; laboratory value was 1340 mg/l; see text for discussion

Figure 3 Map showing the major drainages and general topography of the SUFCO mine lease area.



and northern edges of the mine property, respectively. The incised portion of the North Fork begins in the northwest portion of the mine property and cuts as much as 1,000 feet below the elevation of the plateau in the southeast portion of the mine property.

Six bedrock units are exposed on the mine property from the top of Duncan Mountain and Big Ridge to the bottom of the Quitchupah and Convulsion Canyons (Figures 4 and 5). From top to bottom the rock units are (Doelling, 1972):

(Tertiary-Cretaceous)

North Horn Formation - Variegated shales with subordinate sandstone, conglomerate and freshwater limestone; slope former; approximately 450 feet thick.

(Cretaceous)

Price River Formation, Upper Member - Gray to white gritty sandstone interbedded with subordinate shale and conglomerate; ledge and slope former; 400 to 600 feet thick.

Figure 4 Generalized geologic map of the SUFCO mine lease area. Line A-A' shows the location of cross section shown in Figure 5.

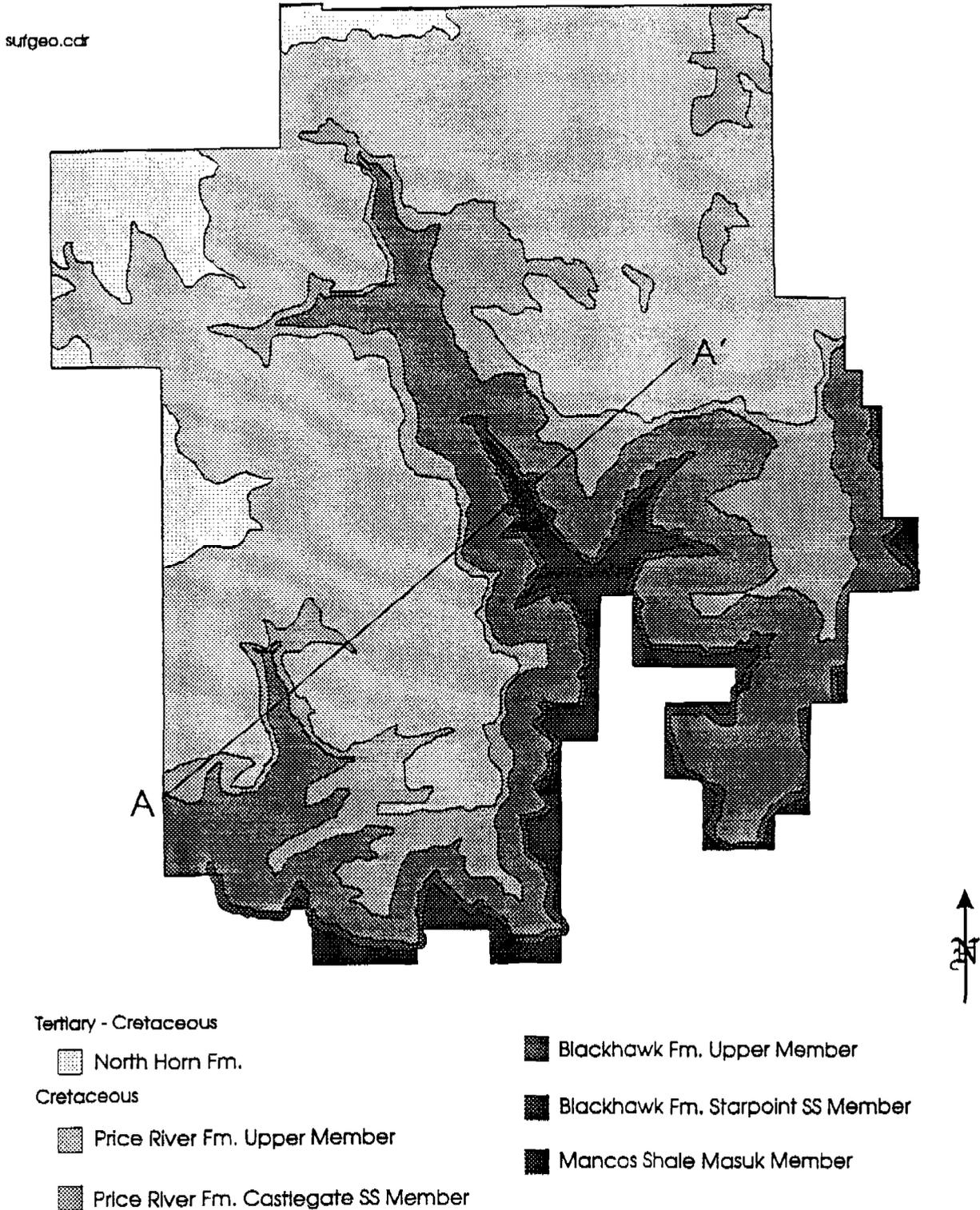
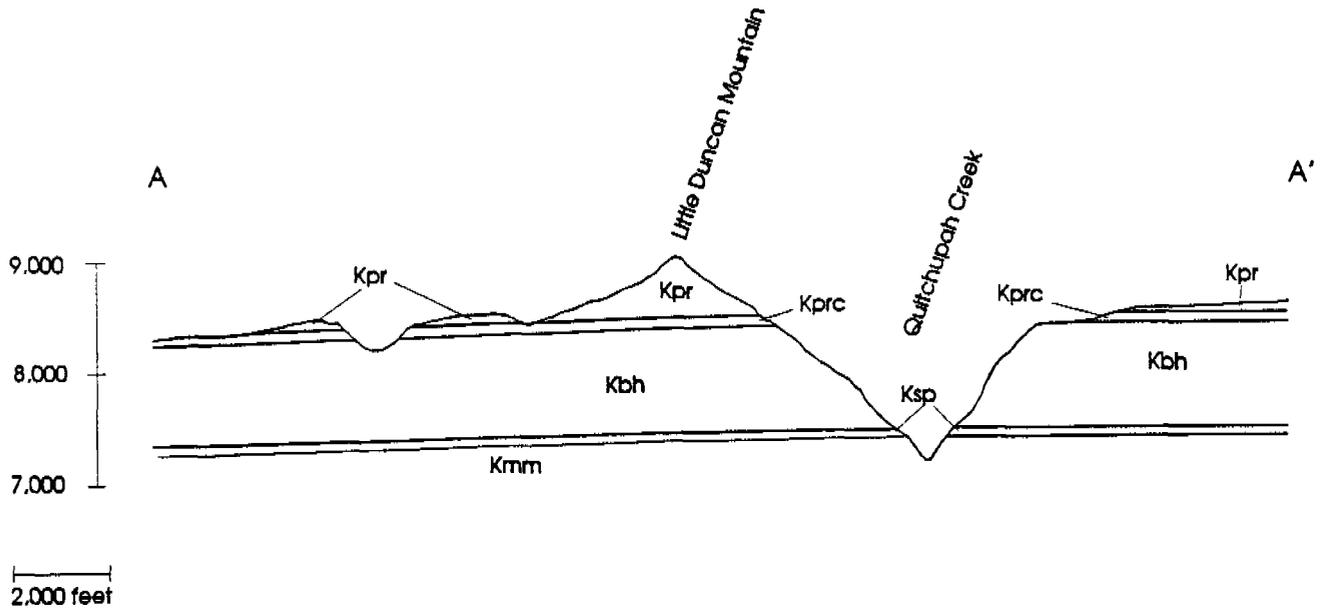


Figure 5 Northeast trending cross section across the SUFCO mine lease area. See Figure 4 for location.

sufxsec2.cdr



Cretaceous

- Kpr - Price River Fm. Upper Member
- Kprc - Price River Fm. Castlegate SS Member
- Kbh - Blackhawk Fm. Upper Member
- Ksp - Blackhawk Fm. Starpoint SS Member
- Kmm - Mancos Shale Masuk Member

Price River Formation, Castlegate Sandstone Member - White to gray, coarse-grained conglomeratic sandstone; cliff former; approximately 100 feet thick.

(Unconformity)

Blackhawk Formation, Upper Member - Yellow to gray, fine- to medium-grained sandstone, interbedded with subordinate gray and carbonaceous shale, thick coal seams; approximately 800 feet thick.

Blackhawk Formation, Star Point Sandstone Member - Yellow-gray, massive cliff-forming sandstone, often in several tongues separated by Masuk Shale; approximately 80 feet thick.

Mancos Shale, Masuk Shale Member - Yellow to blue-gray shale, slope former; thickness exceeds 300 feet.

All bedrock units dip about 1.5° to 2° to the northwest (Figure 4). The Castlegate Sandstone forms the rim of the Canyons. The mine entrance is located along the north cliff face of Convulsion Canyon. The mine entrance is at an elevation of about 7,400 feet and is portalled into the Upper Hiawatha coal seam of the Upper Member of the Blackhawk Formation.

The Upper Member of the Blackhawk Formation was deposited in a delta environment located landward of a barrier-lagoon complex. The Upper Member consists of interbedded sandstone, siltstone, shale, coal and rare limestone. Sandstone comprises approximately 65 percent, siltstone and shale 30 percent, and coal and limestone 5 percent of the thickness of the Upper Member. The sandstones are fine to medium-grained and tabular to lens-shaped with thickness from 2 to 50 feet and widths from 25 to 3,000 feet. The siltstones and shales are commonly interbedded and vary from 1 to 28 feet thick. Siltstones and shales generally bound the sandstones both vertically and horizontally (Marley and others, 1979).

The upper Hiawatha coal seam is located near the bottom of the Upper member of the Blackhawk Formation. The coal seam has an average thickness of 12 feet.

Hydrology and Hydrogeology

The hydrology and hydrogeology of the coal producing region of the southern Wasatch Plateau has been investigated by Danielson and Sylla (1983), Danielson and others (1981), Lines (1985), Lines and Morrissey (1983), Price and Plantz (1987), and Seiler and Baskin (1988). A reconnaissance hydrogeologic investigation

of the Quitchupah Creek region has been performed by Thiros and Cordy (1991).

Two major tributaries of Quitchupah Creek dominate the surface drainage of the mine property and adjacent areas (Figure 3). Both the North Fork of Quitchupah Creek and the flow in Convulsion Canyon are perennial. Stream flows and water quality are monitored by SUFCO. Mine discharge waters issuing from PT003 are discharged into the North Fork of Quitchupah Creek.

Ground-water systems overlying the Hiawatha coal seam are poorly understood. Hydrostratigraphic units have not been defined; however, Thiros and Cordy (1991) have, in general terms, described the water-bearing characteristics of the overlying North Horn Formation, and Castlegate Sandstone and the Blackhawk Formation. A brief summary of their findings follows:

North Horn Formation - The North Horn Formation supports a significant ground-water system in the Ferron Mountain-Flagstaff Peak area, located about 4 miles north of the mine area. In this region about 90 percent of the inventoried springs and seeps discharge from the North Horn Formation. Only 1 spring discharges from the North Horn Formation near the SUFCO mine. Neither Thiros and Cordy (1991) nor Danielson and Sylla (1983)

were able to determine if ground water in the North Horn Formation supports one or more hydraulically continuous aquifers or if the ground water is locally perched.

Thiros and Cordy (1991) concluded that much of the recharge to the North Horn Formation occurs west of the mine area in the upper portions of the Wasatch Plateau.

Price River Formation - Numerous springs issue from both the Upper and Castlegate Sandstone Members of the Price River Formation. Most of the springs issue from the base of the Castlegate Sandstone. Some of the ground waters issuing from the Castlegate Sandstone were identified as discharging from perched ground-water systems. A ground-water sample collected from East Spring (Castlegate Sandstone) had a ^3H content of 28.5 TU indicating ground-water recharge after 1953. Hydrographs of spring discharges show both seasonal and annual responses to precipitation.

Ground-water flow in the Castlegate Sandstone appears to be predominantly bedding controlled. Horizontally continuous water-bearing units have not been identified.

Blackhawk Formation - Thiros and Cordy (1991) found that the Blackhawk Formation is "...usually saturated everywhere within the study area (mine area) except at outcrops at the edge of the plateau, in canyons incised into the plateau, and near the SUFCO mine where dewatering is occurring." They also suggest that impermeable layers within the Blackhawk Formation may create localized perched zones above a saturated zone. They do not, however, provide evidence for a continuous saturated zone or define the stratigraphic location or geometry of such a zone. They further suggest that the Blackhawk Formation is the principal source of water entering the SUFCO mine.

Because surface exposures of the Blackhawk Formation are limited, Thiros and Cordy (1991) suggest that the formation is largely recharged from vertical leakage through fractures in overlying rock units. They do not provide quantitative estimates of annual recharge or evidence supporting the idea of recharge from vertical leakage.

VARIATIONS IN MINE DISCHARGE RATES AND TDS

Ground-water gradients in the mine are downward. Ground water is routinely encountered in the mine roof during mining. Most of this water issues from roof fractures, although some ground water issues from roof bolt holes drilled through the roof coal into the overlying rock units. Ground water is not encountered in the mine floor.

Because roof drip water is moved rapidly through the mine to the surface discharge location (PT003), the long-term record of the mine discharge rate and discharge TDS, combined with observational data regarding changes in roof drip rates, provides valuable insights into the hydrogeology of the Blackhawk Formation above the upper Hiawatha Coal seam.

Variations in Roof Drip and Mine Discharge Rates

The discharge rate of roof drips from recently mined areas tends to decline rapidly. Observations of individual fractures and the 10-year mine discharge hydrograph suggest that roof drip rates from recently mined areas decline rapidly. Although measurements of individual roof drip rates have not been routinely made, mine personnel report rapid declines in drip rates. Estimated changes

in roof drip rates from the following two fractures are believed to be typical of the larger discharges (Kravits, Personal Communication):

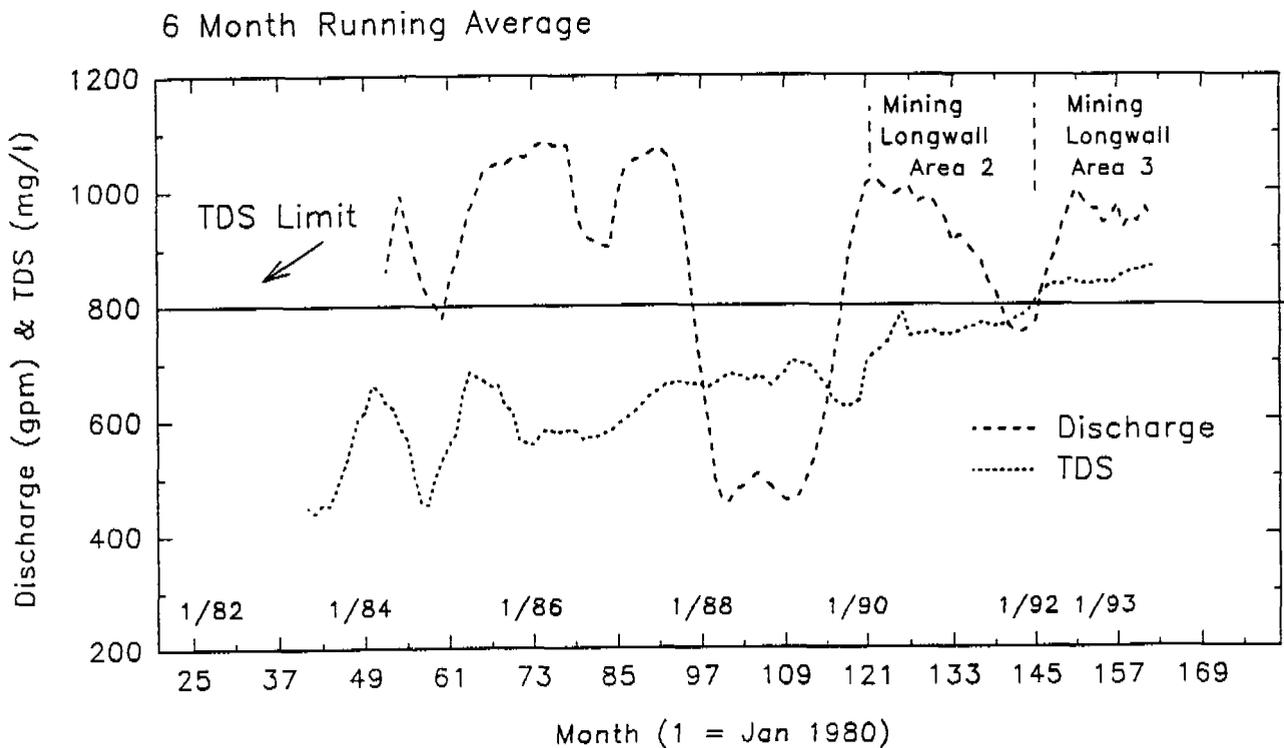
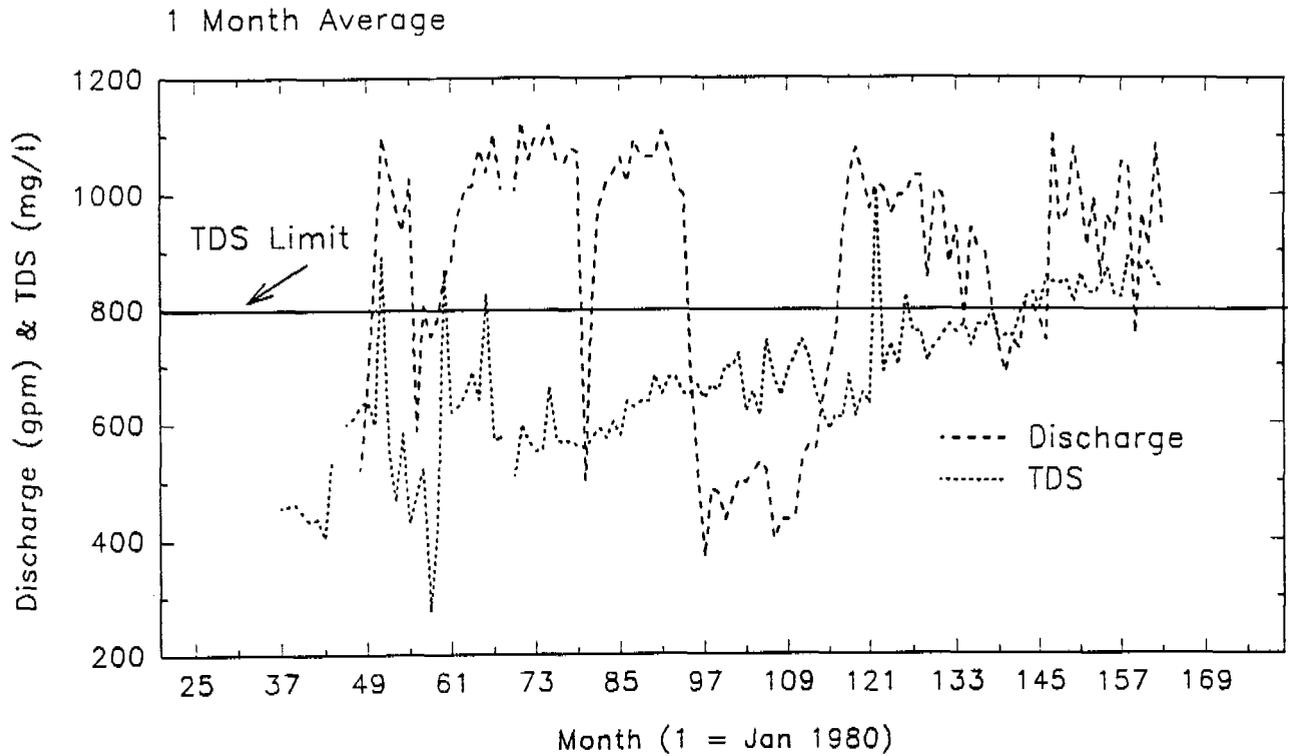
| | |
|--------------------|--------|
| Site (8L4E E3 C63) | |
| 6/6/93 | 40 gpm |
| 7/7/93 | 15 gpm |
| 8/9/93 | 10 gpm |

| | |
|---------------------------|--------|
| Site R2 (Rebuild Station) | |
| 10/11/92 | 50 gpm |
| 2/12/93 | 30 gpm |
| 4/17/93 | 15 gpm |
| 5/19/93 | 5 gpm |
| 7/7/93 | 5 gpm |
| 8/9/93 | 5 gpm |

The 10-year mine discharge hydrograph has been plotted with monthly and 6-month running average data (Figure 6). The 6-month running average method helps smooth out monthly irregularities that result from: 1) changes in the mine floor water management system and, 2) the randomness inherent in taking discharge rate measurements only twice a month. Four conclusions may be drawn from the hydrographs:

1. The significant decline in discharge rate between months 95 and 116 (11/87 to 8/98) are the result of a change in the weir setting. It has subsequently been determined by SUFCO personnel that the weir readings

Figure 6 One month and six month running average discharge and TDS hydrographs of mine discharge water issuing from PT003.



(TDS.SP5)

Table 2 Summary of mean solute and isotopic analysis of roof drip, floor water, and mine discharge water taken during the April 12 and 13, 1993 sampling period.

| Area | T | pH | TDS | TDS | meq/l | | | | | | | o/oo | | | |
|----------------------|------|------|------|-------|-------|------|------|------|------|-------|------|--------|--------|-------|------|
| | | | mg/l | meq/l | Ca | Mg | Na | K | HCO3 | SO4 | Cl | 18O | 2H | 13C | 34S |
| ROOF DRIPS | | | | | | | | | | | | | | | |
| Longwall Area 3 | | | | | | | | | | | | | | | |
| mean | 11.3 | 7.63 | 547 | 19.90 | 4.90 | 4.34 | 0.63 | 0.09 | 6.30 | 3.04 | 0.60 | -16.7 | -126 | -8.3 | 12.0 |
| std | | 0.26 | 80 | 3.09 | 1.03 | 0.67 | 0.07 | 0.02 | 0.93 | 0.51 | 0.23 | 0.4 | 3 | 2.2 | 3.7 |
| Longwall Area 2 | | | | | | | | | | | | | | | |
| mean | 13.5 | 7.6 | 303 | 10.53 | 2.83 | 1.90 | 0.43 | 0.00 | 4.37 | 0.70 | 0.30 | -17.5 | -131.0 | -9.8 | 14.3 |
| std | | 0.0 | 19 | 0.19 | 0.19 | 0.08 | 0.09 | 0.00 | 0.05 | 0.00 | 0.00 | | | | |
| Longwall Area 1 | | | | | | | | | | | | | | | |
| mean | 10.0 | 7.7 | 395 | 15.46 | 4.10 | 3.19 | 0.34 | 0.04 | 6.00 | 1.28 | 0.50 | -17.2 | -125.0 | -9.7 | 9.6 |
| std | | 0.3 | 23 | 1.16 | 0.38 | 0.89 | 0.03 | 0.03 | 0.27 | 0.11 | 0.33 | 0.2 | 1.6 | 1.5 | 1.3 |
| Longwall Areas 1 & 2 | | | | | | | | | | | | | | | |
| mean | 5.75 | 7.66 | 349 | 13.00 | 3.47 | 2.55 | 0.39 | 0.02 | 5.18 | 0.99 | 0.40 | -12.27 | -90.54 | -6.88 | 8.38 |
| FLOOR WATERS | | | | | | | | | | | | | | | |
| mean | 13.1 | 7.59 | 1268 | 38.62 | 8.52 | 6.12 | 4.33 | 0.13 | 6.19 | 12.50 | 0.84 | -12.5 | -92 | -5.9 | 8.7 |
| std | | 0.36 | 647 | 18.37 | 5.60 | 2.42 | 3.31 | 0.05 | 2.06 | 9.54 | 1.06 | 7.2 | 54 | 3.8 | 5.7 |
| MINE DISCHARGE | | | | | | | | | | | | | | | |
| mean | 12.0 | 7.20 | 845 | 26.56 | 5.15 | 4.88 | 3.19 | 0.11 | 5.54 | 7.20 | 0.50 | -17.0 | -129 | -7.1 | 9.9 |
| std | 0.0 | 0.05 | 5 | 0.85 | 0.13 | 0.10 | 0.05 | 0.00 | 0.04 | 0.54 | 0.00 | 0.0 | 1 | 1.1 | |

laboratory content, and the meq l⁻¹ is the sum of the cations and anions.

Saturation index (SI) is a calculated value based on the solute content and temperature of a water sample. It is a measure of the thermodynamic tendency of water either to dissolve or to precipitate a particular mineral and is often useful for evaluating the mineralogy of aquifers through which a ground water has traveled. SI is defined as:

$$SI = \frac{IAP}{K_{eq}} \quad (1)$$

where IAP = the ion activity product and K_{eq} = the equilibrium constant of a specified mineral. Saturation is defined as $\log SI = 0.0 \pm 0.1$. $\log SI < -0.1$ means the water is undersaturated and the water has a thermodynamic tendency to dissolve the mineral. $\log SI > +0.1$ means the water is supersaturated and has a thermodynamic tendency to precipitate the mineral. The saturation index is normally calculated for the discharge temperature of the water. Discharge temperatures for many roof drips were not collected; a value of 11.5 °C has been used for SI calculations for these samples.

The notations used for SI commonly include a subscript to denote the mineral phase. Notations used in this investigation are SI_a (aragonite: $CaCO_3$), SI_c (calcite: $CaCO_3$), SI_d (dolomite: $CaMg(CO_3)_2$), SI_g (gypsum: $CaSO_4 \cdot xH_2O$), SI_{an} (anhydrite: $CaSO_4$) and SI_h (halite: $NaCl$). $\log P_{CO_2}$ is the partial pressure of $CO_2(g)$ and Ca/Mg is the Ca^{2+}/Mg^{2+} molar ratio. The P_{CO_2} content is listed in the tables as $\log P_{CO_2}$ using the units atmospheres. Saturation indices and other parameters have been calculated using the computer code WATEQF (Plummer and others, 1976).

The stable isotopic composition of a sample is reported as the per mil (‰) difference of the sample relative to the isotopic composition of a standard using the delta (δ) notation:

$$\delta = \frac{(R_{\text{sample}} - R_{\text{standard}})}{R_{\text{standard}}} \times 1000 \text{ (‰)} \quad (2)$$

where $R = {}^{18}O/{}^{16}O$, ${}^2H/{}^1H$, ${}^{13}C/{}^{12}C$, and ${}^{34}S/{}^{32}S$. The δ notation is reported in terms of the heavy isotope in the ratio R (i.e., $\delta^{13}C$ for ${}^{13}C/{}^{12}C$).

Other isotopic terms and reference information are discussed as needed.

Overview of Mine Water Geochemistry

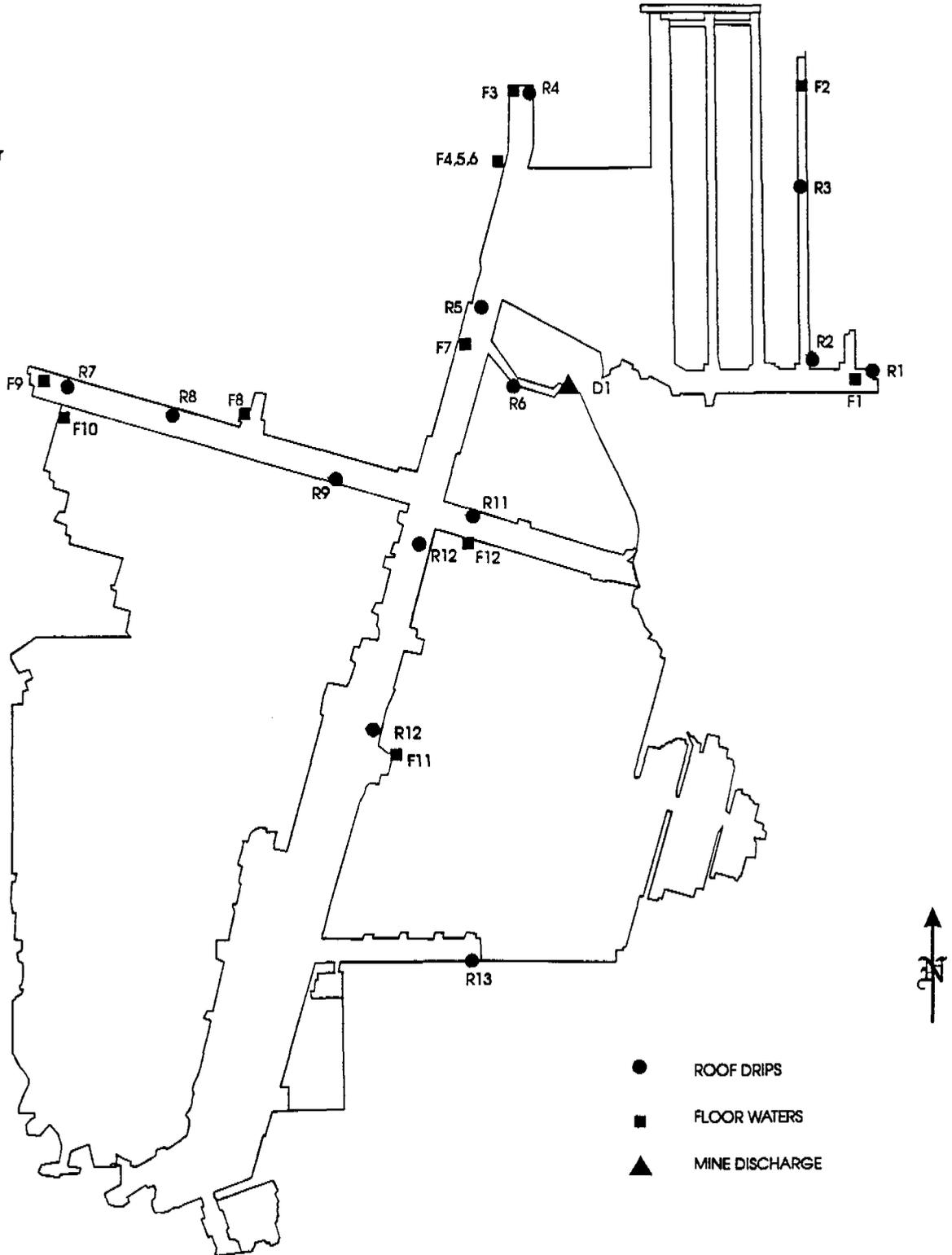
Water quality and isotopic samples were collected from 13 roof drips, 12 floor waters, and the mine discharge. Because these data were collected during two consecutive days, they provide a clear picture of the contribution of each region of the mine to mine discharge TDS.

Sample collection locations are shown on Figure 7, and the geochemical data are listed in Table 1 and are summarized in Table 2. WATEQF calculated saturation indices and other parameters are listed in Table 3. Roof drips, floor waters, and mine discharge water are designated R1 through R13, F1 through F12, and D1, respectively. Sample D1s was collected at the start of the sampling period (4/12/93), and sample D1e was collected at the end of the sampling period (4/13/93).

The roof drips are from the water-bearing horizons in the overlying Blackhawk Formation. Their chemistries are representative of location specific mine waters prior to undergoing chemical reactions in the mine. The chemistries of the floor waters are representative of chemical changes to roof drip water that have occurred at various locations in the mine. The chemistry of the mine discharge water is representative of the weighted average chemistry of all the mine floor water.

Figure 7 Roof drip (R), floor water (F), and mine discharge (D) sampling locations.

suflloc2.cdr



Four distinct waters have been identified in the mine on the basis of their chemical compositions. The characteristics of these groups are described below. The four groups are:

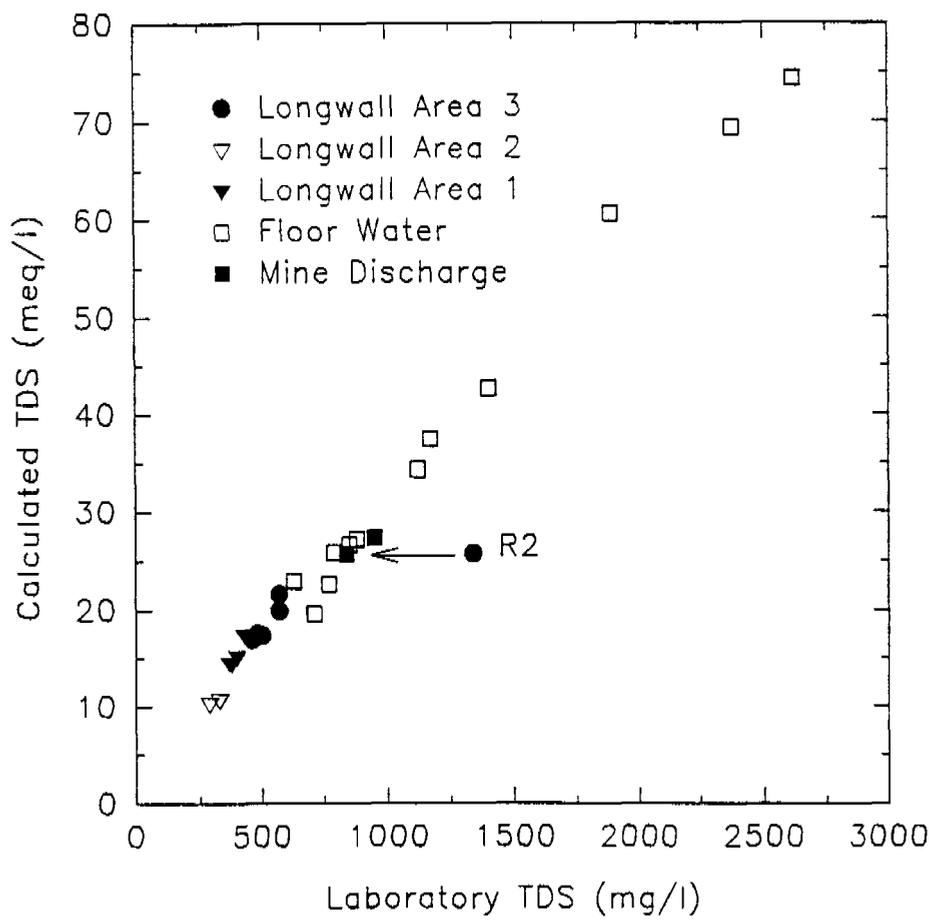
1. Longwall Area 3 roof drips,
2. Longwall Area 2 roof drips,
3. Longwall Area 1 roof drips, and
4. floor waters

Roof Drip Water

Solute Chemistry

Roof drip waters entering the mine issue from three distinct hydrogeochemical units. The hydrogeochemical units have been identified on the basis of TDS and overall solute composition. The TDS (meq l^{-1}) vs. laboratory measured TDS (mg l^{-1}) plot (Figure 8) suggest that the laboratory reported TDS for site R2 (Rebuild Station) is an error. Figure 8 suggests the laboratory reported TDS (1340 mg l^{-1}) is about 2 times as great as the actual value. A sample collected in 3/93 had a TDS of 740 mg l^{-1} . Assuming the TDS of site R2 is about 700 mg l^{-1} , the mean TDS of roof drips in Longwall Area 3 is about 546 mg l^{-1} rather than the calculated 653 mg l^{-1} . A value of 700 mg l^{-1} is therefore

Figure 8 Scatter plot of laboratory reported TDS vs. calculated TDS. Calculated TDS is the sum of the laboratory reported cations and anions in meq l⁻¹. The arrow shows the plotting location of sample R2 after being adjusted for the error in the laboratory reported TDS (mg l⁻¹).



reported in Table 1, and a mean value of 546 mg l⁻¹ is used for analytical purposes in this report.

Although the spatial distribution of roof water collection points does not permit contouring roof water TDS or other chemical parameters, plots of some of the data do exhibit spatial trends. The TDS and SO₄²⁻ concentrations of roof drip waters are shown on Figure 9. Concentrations are lowest in the western portion of the mine area (Longwall Area 2), increase toward the southeast (Longwall Area 1), and are greatest in the northeast (Longwall Area 3). The mean TDS of the roof drip waters in each mining area are statistically distinguishable from each other at the 95 percent confidence interval using a standard T test. The mean TDS and SO₄²⁻ of roof drips in each mining area follow:

| | ----- TDS ----- | | SO ₄ ²⁻ |
|------------------|---------------------|--------------------|-------------------------------|
| | meq l ⁻¹ | mg l ⁻¹ | meq l ⁻¹ |
| Longwall Area 3: | 19.90 | 546 | 3.04 |
| Longwall Area 2: | 10.53 | 303 | 0.70 |
| Longwall Area 1: | 17.42 | 430 | 1.28 |

The overall chemical differences between the Longwall Area roof drips are apparent on the trilinear diagram (Figure 10). The elevated TDS of Longwall Areas 3 and 1 roof drips relative to the

Figure 9 Map showing the TDS and SO_4^{2-} (meq l^{-1}) of roof drip waters collected on April 12 and 13, 1993.

sufrcd2.cdr

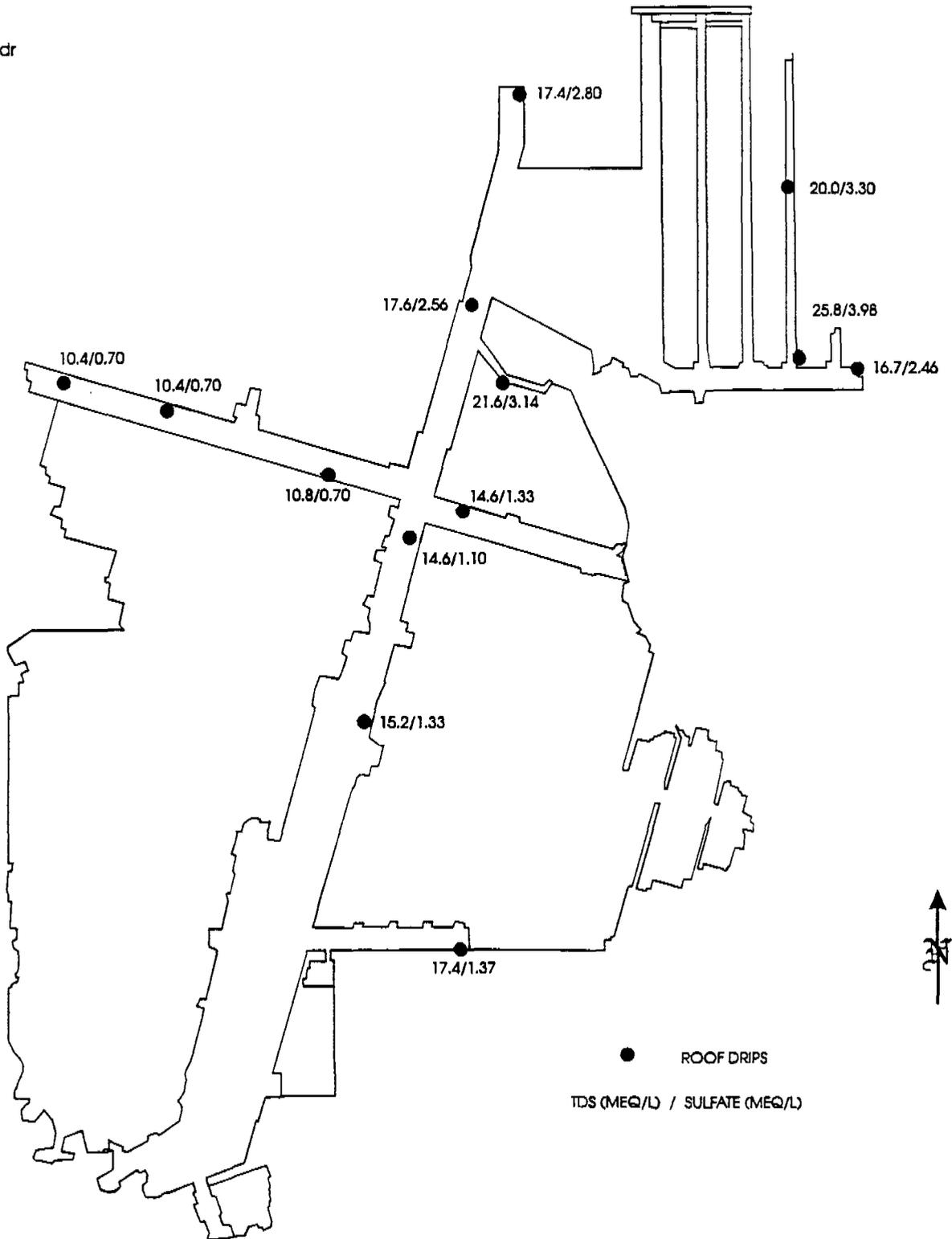
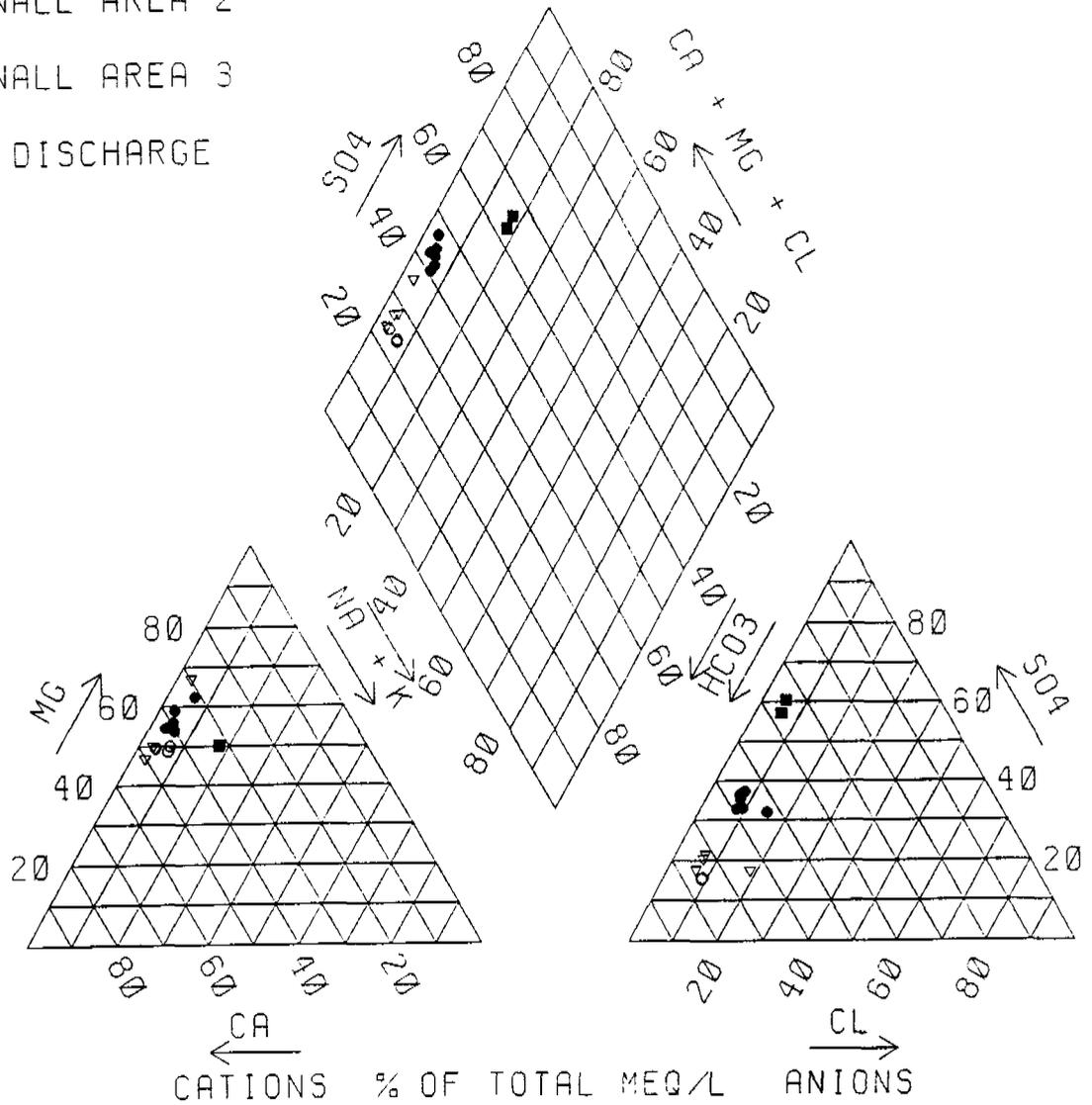


Figure 10 Trilinear diagram of roof drips and mine discharge water collected on April 12 and 13, 1993.

- ▽ LONGWALL AREA 1
- LONGWALL AREA 2
- LONGWALL AREA 3
- MINE DISCHARGE



TDS of Longwall Area 2 are due to the increased concentrations of most major cations and anions. Increased mean concentrations and percentage increases of Longwall Areas 3 and 1 roof drips relative to mean concentrations of Longwall Area 2 roof drips are:

| Constituent | Longwall Area 3 | | Longwall Area 1 | |
|-------------------------------|---|---------------------|---|---------------------|
| | absolute increase (meq l ⁻¹) | percentage increase | absolute increase (meq l ⁻¹) | percentage increase |
| SO ₄ ²⁻ | 2.34 | 334 | 0.58 | 83 |
| Mg ²⁺ | 2.44 | 128 | 1.29 | 68 |
| Ca ²⁺ | 2.07 | 73 | 1.27 | 45 |
| HCO ₃ ⁻ | 1.83 | 41 | 1.63 | 37 |

The mean Ca/Mg ratios of nearly all roof drip waters fall between 1 and 2 (Table 3), suggesting that dolomite is the major source of the elevated Mg²⁺ content. The Ca/Mg ratio in pure dolomite is 1, and the ratio in pure limestone often approaches 20. However, the mean SO₄²⁻ content of Longwall Area 3 drip waters suggests an additional Mg²⁺ source or the occurrence of other chemical reactions. The mean SO₄²⁻ content of 3.04 meq l⁻¹ would have a corresponding Ca²⁺ content and would only leave 1.86 meq l⁻¹ of Ca²⁺ to be contributed from dolomite dissolution. The cor-

Table 3 Log SI and other WATEQF calculated parameters for water samples collected during the April 12 and 13, 1993 sampling period.

| Sample | SIa | SIc | SI d | SIg | SIan | SIh | PCO2 | Ca/Mg |
|------------------------------|-------|-------|-------|-------|-------|-------|-------|-------|
| Roof Drips Longwall Area 3 | | | | | | | | |
| R1 | 0.55 | 0.70 | 1.55 | -1.59 | -1.87 | -8.10 | -2.49 | 0.83 |
| R2 | 0.48 | 0.64 | 1.12 | -1.17 | -1.55 | -8.07 | -2.02 | 1.27 |
| R3 | 0.19 | 0.34 | 0.70 | -1.35 | -1.63 | -8.20 | -1.89 | 1.16 |
| R4 | -0.18 | -0.03 | -0.20 | -1.41 | -1.80 | -8.27 | -1.83 | 1.22 |
| R5 | 0.38 | 0.53 | 1.05 | -1.48 | -1.76 | -8.16 | -2.16 | 1.24 |
| R6 | 0.77 | 0.92 | 1.89 | -1.38 | -1.65 | -7.92 | -2.42 | 1.05 |
| mean | 0.37 | 0.52 | 1.02 | -1.40 | -1.71 | -8.12 | -2.13 | 1.13 |
| std | 0.30 | 0.30 | 0.67 | 0.13 | 0.11 | 0.11 | 0.25 | 0.15 |
| Roof Drips (all other areas) | | | | | | | | |
| R7 | 0.02 | 0.17 | 0.17 | -2.12 | -2.46 | -8.46 | -2.31 | 1.42 |
| R8 | -0.03 | 0.12 | 0.03 | -2.11 | -2.47 | -8.46 | -2.26 | 1.50 |
| R9 | 0.08 | 0.23 | 0.33 | -2.09 | -2.36 | -8.70 | -2.17 | 1.55 |
| R10 | 0.27 | 0.43 | 0.52 | -1.77 | -2.17 | -8.68 | -2.20 | 1.76 |
| R11 | -0.02 | 0.13 | 0.14 | -1.74 | -2.02 | -8.59 | -1.77 | 1.55 |
| R12 | 0.80 | 0.95 | 1.79 | -1.74 | -2.01 | -8.64 | -2.55 | 1.54 |
| R13 | 0.57 | 0.72 | 1.64 | -1.85 | -2.12 | -8.07 | -2.38 | 0.73 |
| mean | 0.24 | 0.39 | 0.66 | -1.92 | -2.23 | -8.51 | -2.23 | 1.44 |
| std | 0.30 | 0.30 | 0.68 | 0.17 | 0.18 | 0.20 | 0.22 | 0.30 |
| Floor Waters | | | | | | | | |
| F1 | 0.47 | 0.62 | 0.78 | -0.07 | -0.34 | -7.19 | -2.45 | 3.61 |
| F2 | 0.48 | 0.63 | 1.28 | -0.87 | -1.14 | -7.32 | -2.13 | 1.17 |
| F3 | -0.14 | 0.01 | -0.39 | -0.31 | -0.70 | -5.92 | -2.07 | 2.45 |
| F4 | 0.56 | 0.72 | 1.26 | -1.22 | -1.61 | -8.10 | -2.62 | 1.32 |
| F5 | 0.15 | 0.30 | 0.69 | -1.05 | -1.32 | -7.53 | -2.09 | 1.00 |
| F6 | 0.60 | 0.76 | 1.53 | -1.03 | -1.41 | -7.48 | -2.72 | 0.91 |
| F7 | 0.43 | 0.59 | 0.95 | -0.56 | -0.99 | -7.26 | -2.48 | 1.31 |
| F8 | 0.72 | 0.87 | 1.75 | -1.33 | -1.66 | -7.61 | -2.59 | 1.01 |
| F9 | 0.41 | 0.56 | 1.09 | -1.33 | -1.68 | -7.62 | -2.21 | 1.08 |
| F10 | -0.02 | 0.13 | 0.19 | -1.26 | -1.59 | -7.40 | -1.54 | 1.18 |
| F11 | 0.19 | 0.34 | 0.78 | -0.88 | -1.15 | -7.68 | -1.49 | 0.96 |
| F12 | 0.10 | 0.25 | 0.60 | -0.53 | -0.86 | -7.27 | -1.38 | 0.85 |
| mean | 0.33 | 0.48 | 0.87 | -0.87 | -1.20 | -7.36 | -2.15 | 1.40 |
| std | 0.26 | 0.26 | 0.56 | 0.40 | 0.41 | 0.50 | 0.44 | 0.78 |
| Mine Discharge | | | | | | | | |
| D1s | -0.27 | -0.11 | -0.28 | -1.01 | -1.39 | -7.47 | -1.73 | 1.06 |
| D1e | -0.18 | -0.02 | -0.11 | -1.08 | -1.45 | -7.47 | -1.83 | 1.05 |
| mean | -0.22 | -0.07 | -0.20 | -1.05 | -1.42 | -7.47 | -1.78 | 1.06 |
| std | 0.04 | 0.04 | 0.09 | 0.03 | 0.03 | 0.00 | 0.05 | 0.00 |

responding Ca/Mg ratio (1.86/4.34) is 0.42, which is considerably less than the ratio of dolomite (i.e., there is too much Mg^{2+}). The source of the elevated Mg^{2+} in Longwall Area 3 roof drips remains problematic.

All roof drip waters are supersaturated with respect to carbonate minerals (aragonite, calcite and dolomite). This means the water would like to precipitate calcium carbonate. Many ground waters attain saturation in the recharge zone, and supersaturated ground waters are not uncommon. The condition of supersaturation can persist in an aquifer because mineral precipitation is often kinetically impaired.

The extent of carbonate mineral supersaturation, particularly dolomite, in these waters is unusual and suggests the ground waters have chemically evolved since they recharged. Ground water can easily become carbonate mineral supersaturated if the aquifer temperature is substantially greater than the temperature of the recharge water. However, such major temperature differences do not occur in the mine waters. The mean temperature of roof drip waters is about $11.5^{\circ}C$, whereas the mean temperature of recharge waters is likely 2 to $5^{\circ}C$.

A more likely cause of the carbonate mineral supersaturation is recharge water at or near carbonate mineral saturation encounter-

ing gypsum in the aquifer. Dissolution of gypsum would cause carbonate mineral supersaturation because of the common ion effect of Ca^{2+} . Gypsum is more soluble than carbonate minerals and would therefore contribute Ca^{2+} ions that would in turn cause carbonate mineral supersaturation.

Stable Isotopic Chemistry

Samples of roof drip waters were collected in an attempt to help characterize the ground-water flow regime of the Blackhawk Formation above the Hiawatha Coal seam. Samples were collected for $\delta^{18}\text{O}$ and $\delta^2\text{H}$ to help evaluate the recharge history of the water, for $\delta^{13}\text{C}$ and $\delta^{34}\text{S}$ to help evaluate the evolution of the solute chemistry of the waters, and for the radioactive isotopes ^3H and ^{14}C to help determine the age of the water.

Oxygen-18 ($\delta^{18}\text{O}$) and Hydrogen-2 ($\delta^2\text{H}$)

Worldwide, the $\delta^2\text{H}$ and $\delta^{18}\text{O}$ of precipitation (rain and snow) generally follow the empirical relationship:

$$\delta^2\text{H} = s(\delta^{18}\text{O}) + d \text{ (}\text{‰}\text{)} \quad (3)$$

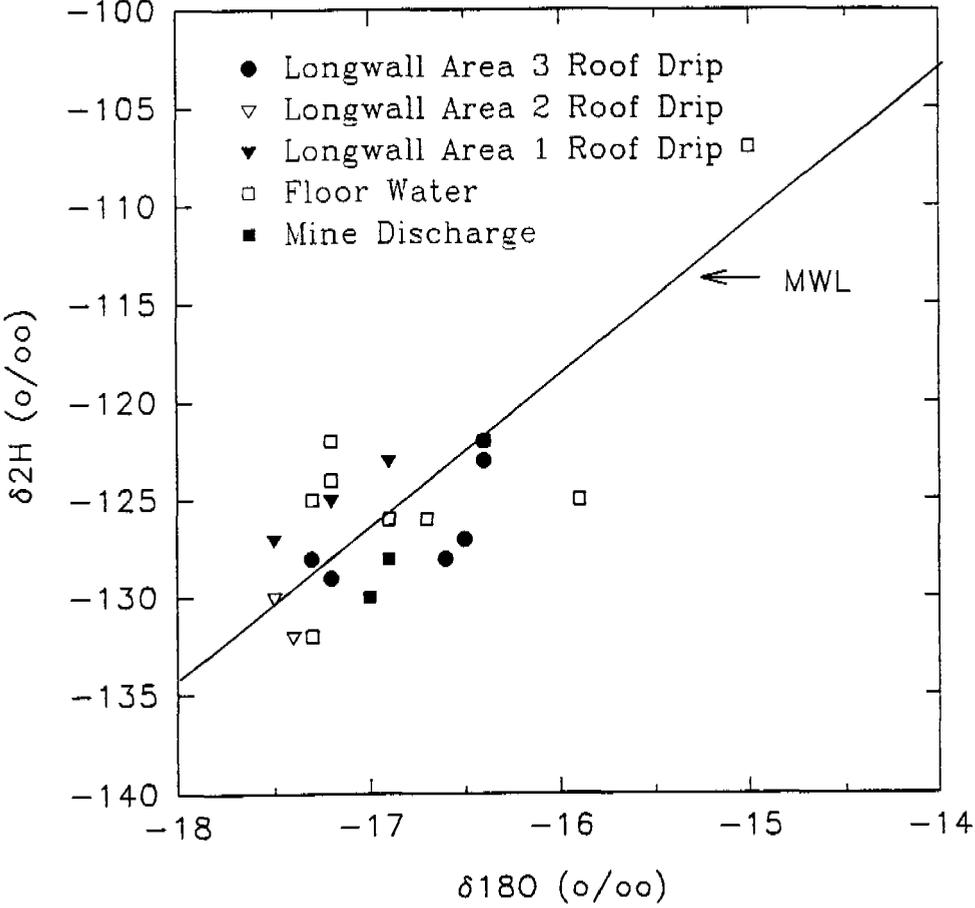
where s is the slope and d is the deuterium excess (Merlivant and Jouzel, 1983). Craig (1961) and Dansgaard (1964) have shown that, on the global scale, s approximates 8 and d approximates 10 for coastal meteoric water. The Meteoric Water Line (MWL) is therefore defined as:

$$\delta^2\text{H} = 8(\delta^{18}\text{O}) + 10 \text{ (}\text{‰}\text{)} \quad (4)$$

The $\delta^{18}\text{O}$ and $\delta^2\text{H}$ composition of roof drips fall in the narrow range of -16.4 to -17.5 ‰ and from -122 to -132 ‰, respectively (Table 1; Figure 11). All of the data cluster about the MWL, and the data do not exhibit thermal isotopic shift in $\delta^{18}\text{O}$ or evaporative shifts in both $\delta^{18}\text{O}$ and $\delta^2\text{H}$. This means the water recharges from the infiltration of rain or snow. The waters have not upwelled along deep seated faults and are not residual connate water from marine or backwater evaporative sedimentary environments.

The mean isotopic composition of data from Longwall Area 3 is slightly more positive than is the mean isotopic composition from the other mining areas. More positive compositions are usually correlated to warmer recharge temperatures. However, the tight cluster of the data and the results of statistical T-tests preclude a definitive analysis. The means of the recharge waters do not vary at the 95% percent confidence interval.

Figure 11 Plot of $\delta^{18}\text{O}$ and $\delta^2\text{H}$ data relative to the meteoric water line (MWL).



(2H180x.SP5)

Carbon-13 ($\delta^{13}\text{C}$)

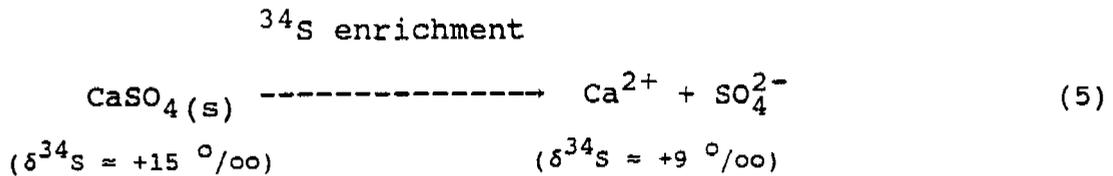
Roof drip waters have $\log \text{PCO}_2(\text{g})$ values (Tables 1 and 2) that are consistent with the dissolution of carbonate minerals in the presence of soil zone $\text{CO}_2(\text{g})$. Most ground water acquires 50 percent of its carbon from soil zone water and 50 percent of its carbon from the dissolution of carbonate minerals in the soil zone or aquifer skeleton. Because the $\delta^{13}\text{C}$ of marine carbonate minerals is about 0 ‰ (Muller and Mayo, 1986), most ground waters have a $\delta^{13}\text{C}$ of ≈ -10 to -13 ‰. The $\delta^{13}\text{C}$ of many roof drip waters is less than anticipated and may reflect carbonate mineral precipitation and dissolution reactions in the upper member of the Blackhawk Formation.

We had hoped the $\delta^{13}\text{C}$ data would help distinguish regions of roof drip water from each other, but the scatter of the data was too great to do so.

Sulfur-34 ($\delta^{34}\text{S}$)

The $\delta^{34}\text{S}$ data indicate that all roof drip water sulfate is derived from the dissolution of gypsum and/or anhydrite. The anticipated range of $\delta^{34}\text{S}$ values in Mesozoic early Tertiary gypsum and anhydrite is +10 to +20 ‰ (Holser and Kaplan, 1966). At

non-thermal aquifer temperatures, isotopic fractionation accompanying gypsum dissolution may be represented as:



where the value $\delta^{34}\text{S} \approx +15 \text{ } \text{‰}$ has been arbitrarily selected. The typical $\delta^{34}\text{S}$ value of magmatic pyrite is about $0 \text{ } \text{‰}$ (Faure, 1986). A $\delta^{34}\text{S}$ of $-2.2 \text{ } \text{‰}$ has been reported for pyrite in the Park City District (Thode and others, 1961) and Mayo and Klauk (1991) found a mean $\delta^{34}\text{S}$ of $+1.3 \text{ } \text{‰}$ in ground water from non-carbonate (crystalline rock) aquifers in north central Utah.

In addition to identifying the source of the roof drip SO_4^{2-} , we had hoped to use the $\delta^{34}\text{S}$ data to help distinguish regions of roof drip water from each other, but the scatter of the data were too great to do so. However, the large scatter of data do provide insight into the ground-water systems in the overlying Blackhawk Formation. The wide range of $\delta^{34}\text{S}$ isotopic compositions suggests that roof drip waters issue from numerous discrete ground-water systems that are not hydraulically connected. If roof drips issue from a single ground-water system, the $\delta^{34}\text{S}$ compositions of roof dip waters would have been similar or would have exhibited a spatial trend.

Age of Roof Drip Ground Water

Tritium (^3H)

The radioactive isotopes tritium (^3H) and carbon-14 (^{14}C) were collected at site R2 to estimate the age of roof drip water, and ^3H was collected at 3 other locations. Tritium (^3H), the radioactive isotope of hydrogen, has been used in ground-water investigations to differentiate between ground waters which recharged prior to or after the advent of atmospheric thermonuclear weapons testing. Tritium, whose half life is 12.26 years, forms naturally in the upper stratosphere by the interaction of ^{14}N with cosmic ray neutrons according to the reaction:



Tritium is rapidly incorporated into water molecules and is removed from the atmosphere by precipitation.

Prior to the advent of atmospheric thermonuclear weapons testing in 1952, tritium activity in precipitation ranged from 4 to 25 tritium units (TU). One TU equals one ^3H atom per 10^{18} hydrogen atoms. In mountainous areas, larger natural concentrations have been observed (Fontes, 1983). During the peak of atmospheric

weapons testing, tritium levels in precipitation rose to more than 2200 TU in some northern hemisphere locations (Fontes, 1983). As of 1987, the ^3H concentrations in rain water varied from 25 to 50 TU. Unpublished data of 1991 and 1992 snow samples collected in the central Wasatch Range have TU concentrations greater than 20 TU.

The ^3H content of roof dip waters indicate that ground water entering the mine recharged prior to 1952. The ^3H contents of samples are: R2 < 3 TU (which is the detection limit for the analysis of that sample), R8 and R12 is 1.1 ± 2.4 and, sample R5 is 3.3 ± 2.4 (Table 1). The TU content of a sample collected in the mine by Thiros and Cordy (1991) was < 1 TU, which was the detection limit for that analysis.

Carbon-14 (^{14}C)

Carbon-14, the radioactive isotope of carbon, has a half-life of 5730 ± 30 years (Godwin, 1962). Carbon-14 is produced in the upper atmosphere by a variety of reactions that involve the collision of cosmic radiation (neutrons) with stable isotopes of nitrogen, oxygen, and carbon. The most important of these reactions is between neutrons and ^{14}N according to the reaction:



where n is a neutron and p is a proton (Libby, 1955). Carbon-14 is incorporated into $\text{CO}_2(\text{g})$ and rapidly mixes throughout the atmosphere and hydrosphere where steady state equilibrium between ${}^{14}\text{C}$ production and ${}^{14}\text{C}$ decay is attained (Faure, 1986).

The pre-industrial revolution atmospheric ${}^{14}\text{C}$ content has been assigned the steady state value of 100 percent modern carbon (pmc). The burning of fossil fuels and the advent of atmospheric thermonuclear weapons testing greatly altered the ${}^{14}\text{C}$ activity in the post-industrial revolution atmosphere. Burning of fossil fuels, whose ${}^{14}\text{C}$ had previously completely decayed away, decreased the ${}^{14}\text{C}$ content in the troposphere in the northern hemisphere by about 3% (Houtermans and others, 1967). Atmospheric weapons testing greatly increased the atmospheric ${}^{14}\text{C}$ activity by the mid 1960's (Ferrofsky and Polyakov, 1982).

The post-industrial revolution atmospheric ${}^{14}\text{C}$ perturbations and laboratory measurement error in measuring the ${}^{14}\text{C}$ content of ground water make the reliable lower limit for ${}^{14}\text{C}$ dating about 450 years. The upper limit of ${}^{14}\text{C}$ dating, using conventional laboratory analytical methods, is about 35,000 years.

Estimating the age of dead wood or other organic carbon is relatively simple. The ^{14}C activity of pre-industrial revolution organic material is assumed to be 100 pmc. The radiocarbon date is then corrected for systematic variations in atmospheric ^{14}C that have been established by comparing tree ring dates of the wood of sequoia and bristlecone pines with their corresponding radiocarbon ages (LaMarche and Harlan, 1973; Michael and Ralf, 1970).

Estimating the radiocarbon age of ground waters is not as straightforward as estimating the age of dead organic matter. Ground water acquires carbon from numerous sources, many of which had an initial ^{14}C activities of less than 100 pmc. The ^{14}C content of ground water is affected by four factors:

- 1) the addition of "live" carbon (i.e., $^{14}\text{C} \approx 100$ pmc) from the biogenic production of $\text{CO}_2(\text{g})$ in the soil zone,
- 2) the addition of "dead" carbon from weathering of minerals in the soil zone and the dissolution of carbonate minerals in the soil zone or aquifer (i.e., $^{14}\text{C} \approx 0$ pmc),
- 3) the addition of "dead" carbon from the soil or aquifer during isotopic exchange reactions, and
- 4) the addition of both "live" and "dead" carbon by other processes.

The crux of dating ground water is estimating the initial ^{14}C activity (A_0) of the water at the time of recharge. This may be accomplished by using the solute and isotopic chemistries of the ground water and by applying correction procedures. Correction procedures for estimating A_0 are in the form of mathematical equations that attempt to account for the contribution of "dead" carbon and ^{14}C from various sources, and for the effects of the isotopic exchange and fractionation processes.

The ^{14}C activity of the Rebuild Station roof drip sample (R2) is 7.2 ± 1.2 pmc, and the $\delta^{13}\text{C}$ of the sample was -8.5 ‰. Mean ground-water residence time of the sample (its age) was calculated using a proprietary computer code. The code incorporates 6 different mathematical models as described by Fontes and Garnier (1979). Based on modeling results, the calculated age of sample R2 is 15,500 to 16,500 years. This means the water in the Blackhawk Formation overlying the mine has been isolated from surface recharge since then.

Measured and estimated data used in the ground-water age calculation include: $\delta^{13}\text{C}$ of the sample = -8.5 ‰ (measured); $\delta^{13}\text{C}$ of the carbonate minerals in the recharge zone = 0 ‰ (estimated); $\delta^{13}\text{C}$ of the CO_2 (g) in the soil zone = -20 ‰ (estimated); ^{14}C of the sample = 7.2 pmc (measured); ^{14}C of aquifer minerals = 0 pmc (estimated); activity of HCO_3^{2-} in the water = 0.087956

(calculated). Estimate values are consistent with values found in the mountainous terrains of Utah and elsewhere.

Floor Water

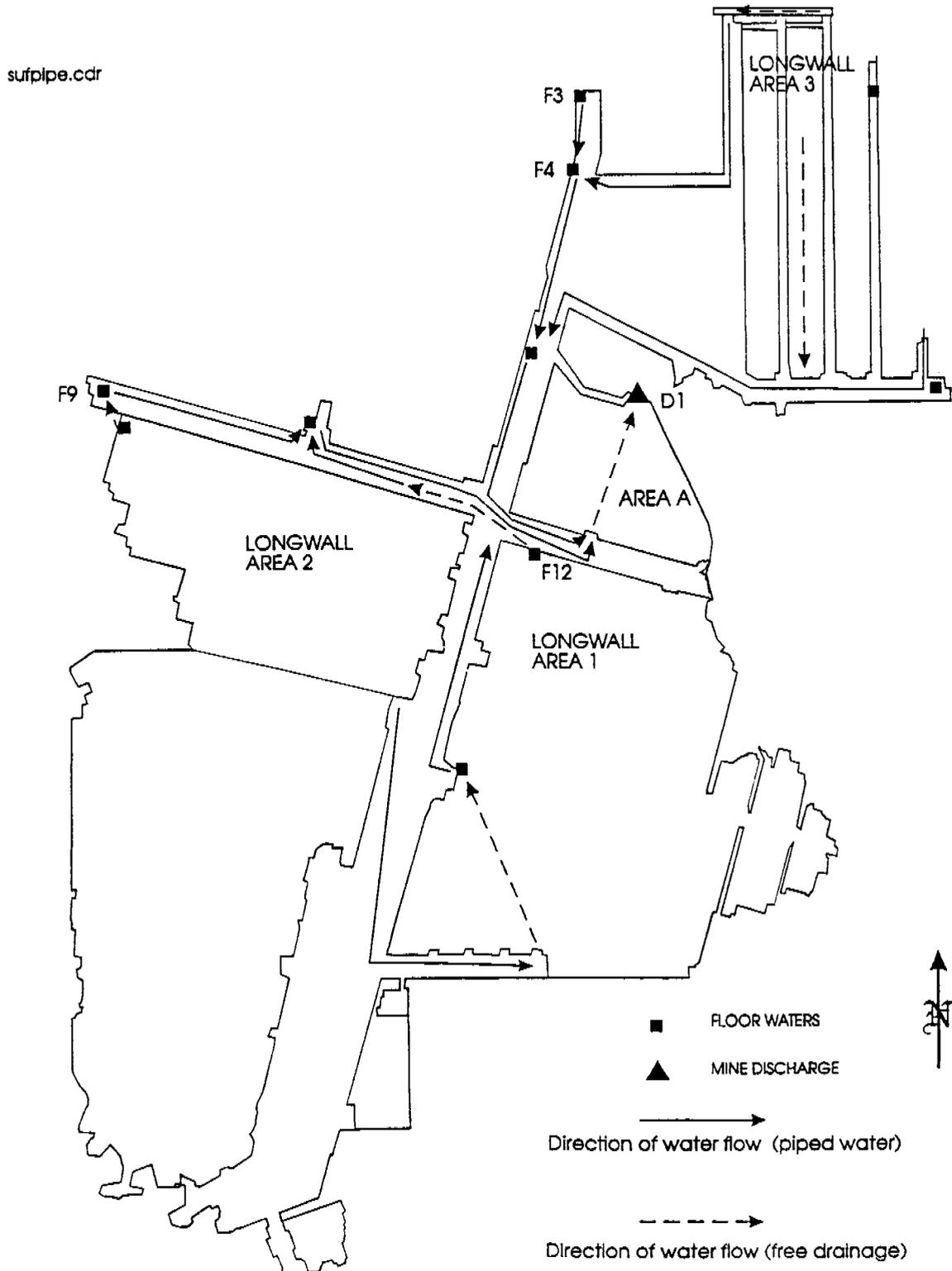
A schematic of the floor water management system during the sampling period (April 12 and 13) is shown on Figure 12. Most of the floor water is conveyed in pipes. Water moves along the floor in Longwall Areas 1, 2 and 3, and across the floor of an old room and pillar mined area before discharge at PT003. Floor water from Longwall Areas 1 and 2 discharges into open tunnels from seals that are used to close the longwall areas.

A summary of the floor water management scheme during the April 1993 sampling follows:

Longwall Area 1

Water discharges from this closed section of the mine at site F12 (1L6E North Seal). This water flows first along the floor and then is piped to the collection sump at F8 (6 North Sump). From sump (F8) it is piped to closed Room and Pillar area A, where it flows along floor of the area and ultimately discharges at PT003.

Figure 12 Diagram of the floor water management system on April 12 and 13, 1993. Sumps F3 and F4 are the collection locations for Longwall Area 3, sump F9 is the collection location for Longwall Area 2, and sump F12 is the collection location for Longwall Area 1. Location D1 is the mine discharge point (PT003).



Water discharging from F11 (6East Seals) flows along the mine floor to the mine process water sumps and thus does not go directly to Area A where it would be discharged.

Longwall Area 2

Water discharges from this closed section of the mine at site F10 (1L North Main Seal) and flows over the mine floor to F9 (3 West Sump). This water is piped from F9 to the collection sump at F8 where it mixes with water from F12.

Longwall Area 3

Water from the active mining area is collected at two locations. Floor water in the northern portion of the area is collected and piped to site F4 (North Mains #4 sump) where it mixes with water from F3 (North Mains face pump). Floor water from the southern portion of the area is piped to site F7 (North Mains #3 sump) and mixes with water from F1 (4 East face pump). Water from both North Mains #3 and North Mains #4 sumps are then piped separately to closed room and pillar Area A, where they mix with water from the sump at F8. All

of the floor waters mix in a large sump in the north part of Area A and ultimately discharge at D1 (mine discharge PT003).

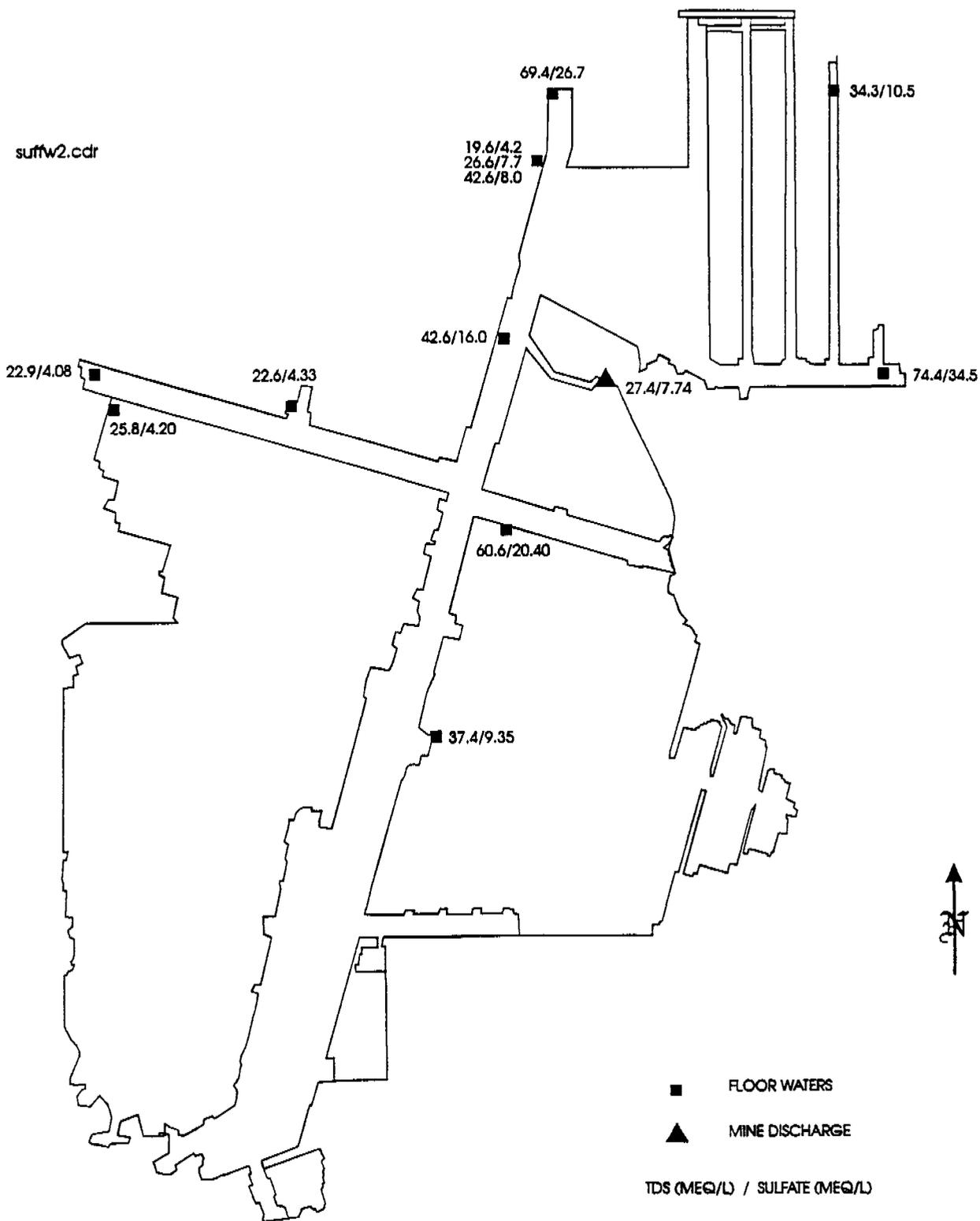
The TDS of floor waters are highly variable, ranging from about 20 to 75 meq l⁻¹ (Table 1; Figures 8 and 13). The chemistry of the floor water at various locations reflect:

- 1) chemical reactions between incoming roof drip water with gypsum rock dust, longwall emulsion, dolomite crushed rocks, and other materials introduced into the mine, and
- 2) the mixing of floor waters from other locations in the mine.

The TDS of individual floor waters is not particularly enlightening when examined in the absence of flow rate data, because the TDS of the mine discharge water is the integrated mean of the flow of floor waters weighted for TDS at critical locations in the mine. Water quality samples and flow rate measurements were made at four (4) critical locations during the April 1993 sampling. Floor water quality samples were also collected at sites where flow measurements were not made.

Water discharge and water quality budgets have been calculated for mine floor waters during the April 1993 sampling (Table 4).

Figure 13 Map showing the TDS and SO_4^{2-} (meq l^{-1}) of floor waters collected on April 12 and 13, 1993.



The contribution to the total mine discharge from the three mining areas was accounted for by flow measurements and water quality samples collected at the 4 critical locations. The critical sampling locations are:

Longwall Area 3 - sites F4 and F7

Longwall Area 2 - site F9

Longwall Area 1 - site F12

In Table 4 the %Q and %TDS columns list the percentage of the total mine discharge and TDS, respectively, which are contributed from each location to the total mine discharge rate and discharge TDS. The TDS, solute, and $\delta^{13}\text{C}$ and ^{34}S contents of each of floor waters are also listed. The TDS contribution from each location was calculated by multiplying the percentage of the total discharge attributed to the sample location by the solute or isotopic content of the water sample at the site. The calculated water quality of the mine discharge is the sum of the calculated contributions from each sampling location. The calculated TDS of the mine discharge was within about 3 percent of the measured TDS of discharge water from the mine.

The excellent agreement between calculated and measured TDS means that the data collected at the four critical sampling locations: 1) are representative of the 3 mining areas, 2) can be used to

Table 4 Comparisons of calculated mass and isotopic compositions of mine discharge water with floor waters representative of the 3 long wall mining areas.

| Source | % Q | TDS | | % TDS | | Ca | | Mg | | Na | | K | | HCO ₃ | | SO ₄ | | Cl | |
|----------------------|-----|-----------|---------------|-------------|-------------|----------|---------------|----------|---------------|----------|---------------|---------|---------------|------------------------|---------------|-----------------------|---------------|----------|---------------|
| | | TDS meq/l | Contrib meq/l | TDS Contrib | TDS Contrib | Ca meq/l | Contrib meq/l | Mg meq/l | Contrib meq/l | Na meq/l | Contrib meq/l | K meq/l | Contrib meq/l | HCO ₃ meq/l | Contrib meq/l | SO ₄ meq/l | Contrib meq/l | Cl meq/l | Contrib meq/l |
| ----- | | | | | | | | | | | | | | | | | | | |
| Longwall area 3 | | | | | | | | | | | | | | | | | | | |
| F4 | 44 | 19.60 | 8.62 | 31.4 | 5.00 | 2.20 | 3.80 | 1.67 | 0.90 | 0.40 | 0.10 | 0.04 | 5.20 | 2.29 | 4.20 | 1.85 | 0.40 | 0.18 | |
| F7 | 17 | 42.62 | 7.25 | 26.4 | 9.90 | 1.68 | 7.50 | 1.28 | 3.49 | 0.59 | 0.12 | 0.02 | 4.94 | 0.84 | 16.00 | 2.72 | 0.77 | 0.13 | |
| Longwall area 2 | | | | | | | | | | | | | | | | | | | |
| F9 | 32 | 22.90 | 7.33 | 26.7 | 4.15 | 1.33 | 3.85 | 1.23 | 3.30 | 1.06 | 0.09 | 0.03 | 7.13 | 2.28 | 4.08 | 1.31 | 0.34 | 0.11 | |
| Longwall area 1 | | | | | | | | | | | | | | | | | | | |
| F12 | 7 | 60.60 | 4.24 | 15.5 | 10.90 | 0.76 | 12.80 | 0.90 | 5.70 | 0.40 | 0.20 | 0.01 | 10.10 | 0.71 | 20.40 | 1.43 | 0.50 | 0.04 | |
| Calculated discharge | | | 27.44 | | | 5.97 | | 5.08 | | 2.44 | | 0.11 | | 6.12 | | 7.30 | | 0.45 | |
| Measured discharge | | | 26.56 | | | 5.15 | | 4.88 | | 3.19 | | 0.11 | | 5.54 | | 7.20 | | 0.50 | |
| Difference | | | 0.88 | | | 0.82 | | 0.20 | | -0.75 | | 0.00 | | 0.58 | | 0.10 | | -0.05 | |
| % difference | | | 3.31 | | | 16.00 | | 4.00 | | -23.38 | | 0.00 | | 10.40 | | 1.41 | | -9.86 | |

| Source | % Q | 13C | | 34S | |
|----------------------|-----|------------|----------------|------------|----------------|
| | | 13C (o/oo) | Contrib (o/oo) | 34S (o/oo) | Contrib (o/oo) |
| ----- | | | | | |
| Longwall area 3 | | | | | |
| F4 | 44 | -9.30 | -4.09 | 8.30 | 3.65 |
| F7 | 17 | -5.40 | -0.92 | 12.20 | 2.07 |
| Longwall area 2 | | | | | |
| F9 | 32 | -11.70 | -3.74 | 10.60 | 3.39 |
| Longwall area 1 | | | | | |
| F12 | 7 | -8.10 | -0.57 | 6.80 | 0.48 |
| Calculated discharge | | | -9.32 | | 9.59 |
| Measured discharge | | | -7.10 | | 9.90 |
| Difference | | | -2.22 | | -0.31 |
| % difference | | | 31.28 | | -3.09 |

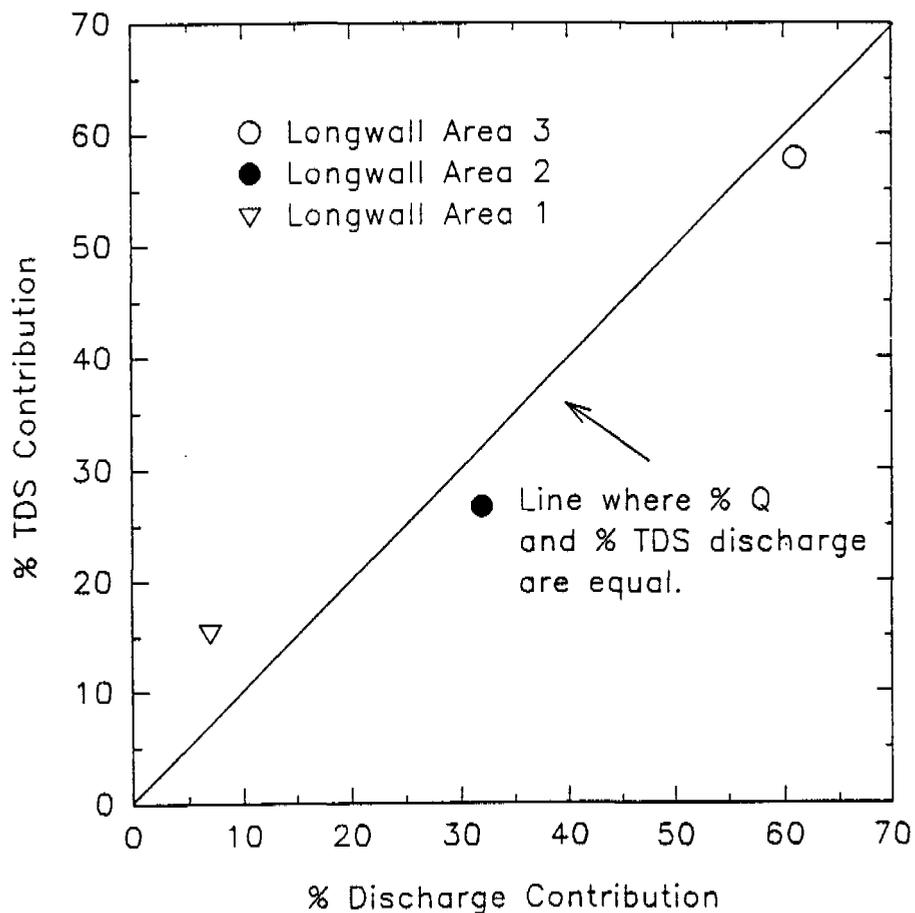
evaluate chemical reactions occurring in each region of the mine and, 3) can be used to calculate the mass contribution from each region of the mine to the overall TDS of the mine discharge water.

A plot of the percent TDS contribution versus the percent discharge contribution from the three longwall areas is shown on Figure 14. The diagonal line indicates plotting locations where percent TDS and percent discharge contributions are equal. The diagonal line may be thought of as representing a TDS of about 850 mg l^{-1} or about 27 meq l^{-1} , because the mine discharge water contains 100% of both the discharge and TDS (i.e., PT003 would plot at 100% on both axes). Points which plot below the line have a TDS which is less than 850 mg l^{-1} , and points that plot above the line have a TDS which is greater than 850 mg l^{-1} . Floor water issuing from Longwall Areas 2 and 3 have TDS contents slightly less than that of the mine discharge, and water issuing from Longwall Area 1 has a TDS content considerably greater than that of the mine discharge.

GEOCHEMICAL EVOLUTION OF MINE WATER

Ground water entering the mine undergoes major chemical changes as it moves through the active and old mining areas. Changes in

Figure 14 Plot of % TDS vs. % discharge contribution from each of the longwall mining areas relative to the total TDS and discharge of the mine discharge water. Data are representative of the April 1993 sampling period.



(%TDSQ.SP5)

the solute chemistry of roof drip waters due to chemical reactions in the longwall areas are tabulated on Table 5. Because Longwall Areas 1 and 2 are now inaccessible, the chemical compositions of roof dip waters in these areas are somewhat uncertain. The chemical compositions of roof dips in the older mining areas have been assigned the mean values of the roof drips in the adjacent open mine areas. The following discussion is predicated on the idea that the assigned roof drip waters reasonably represent the chemistry of the roof drip water in each mining area.

Significant changes in Ca^{2+} , Mg^{2+} , Na^+ , HCO_3^{2-} , and SO_4^{2-} concentrations and in the saturation indices (SI) of calcite, dolomite, and gypsum are observed in the floor waters of all mining areas relative to the mean compositions of the roof drips in their respective areas (Table 5; Figure 15). In the table and figure a positive change for a particular ion means that the floor water has a greater concentration of that ion than the incoming ground water. A positive change in SI means that the water has become more saturated with respect to the particular mineral. The mean SI's of roof drip waters may differ slightly from those listed in Table 3, because the SI's in Table 5 were calculated using the mean water chemistry of the roof drip water, whereas the mean values in Table 3 are the calculated mean of the individual SI's.

Table 5 Comparisons of mining area roof drip and floor water solute compositions.

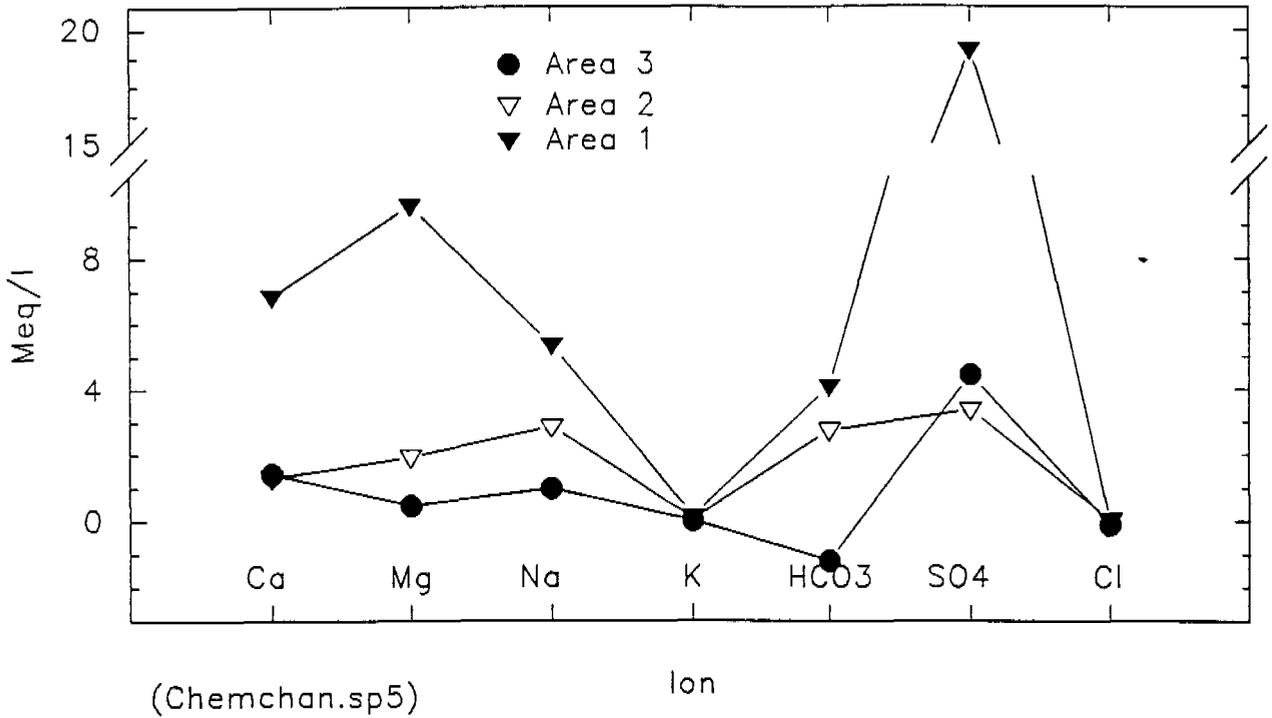
----- Longwall Area 3 -----

| Parameter | Mean | F4 | F4 | F7 | F7 | Mean | Change |
|--------------|-----------|-------|---------|-------|---------|--------------------------|--------|
| | Roof Drip | | x 72.1% | | x 29.7% | Floor Water (F4 + F7) | |
| Temp (C) | 11.00 | 11.00 | 7.93 | 7.50 | 2.09 | 10.02 | |
| pH | 7.63 | 8.00 | 5.77 | 7.80 | 2.18 | 7.94 | 0.31 |
| Ca (meq/l) | 4.90 | 5.00 | 3.61 | 9.80 | 2.73 | 6.34 | 1.44 |
| Mg (meq/l) | 4.34 | 3.80 | 2.74 | 7.50 | 2.09 | 4.83 | 0.49 |
| Na (meq/l) | 0.63 | 0.90 | 0.65 | 3.49 | 0.97 | 1.62 | 0.99 |
| K (meq/l) | 0.09 | 0.10 | 0.07 | 0.12 | 0.03 | 0.11 | 0.02 |
| HCO3 (meq/l) | 6.30 | 5.20 | 3.75 | 4.94 | 1.38 | 5.13 | -1.17 |
| SO4 (meq/l) | 3.04 | 4.20 | 3.03 | 16.00 | 4.46 | 7.49 | 4.45 |
| Cl (meq/l) | 0.60 | 0.40 | 0.29 | 0.77 | 0.21 | 0.50 | -0.10 |
| SiC | 0.42 | | | | | 0.68 | 0.26 |
| SiD | 0.72 | | | | | 1.18 | 0.46 |
| SiG | -1.36 | | | | | -0.94 | 0.42 |

| Parameter | ----- Longwall Area 2 ----- | | | ----- Longwall Area 1 ----- | | |
|--------------|-----------------------------|---------------------------|--------|-----------------------------|----------------------------|--------|
| | Mean Roof Drip | Mean Floor Water F9 | Change | Mean Roof Drip | Mean Floor Water F12 | Change |
| Temp (C) | 13.50 | 14.00 | | 10.00 | 15.00 | |
| pH | 7.60 | 7.75 | 0.15 | 7.70 | 7.05 | -0.65 |
| Ca (meq/l) | 2.83 | 4.15 | 1.32 | 4.10 | 10.90 | 6.80 |
| Mg (meq/l) | 1.90 | 3.85 | 1.95 | 3.19 | 12.80 | 9.61 |
| Na (meq/l) | 0.43 | 3.30 | 2.87 | 0.34 | 5.70 | 5.36 |
| K (meq/l) | 0.00 | 0.09 | 0.09 | 0.04 | 0.20 | 0.16 |
| HCO3 (meq/l) | 4.37 | 7.13 | 2.76 | 6.00 | 10.10 | 4.10 |
| SO4 (meq/l) | 0.70 | 4.08 | 3.38 | 1.28 | 20.40 | 19.12 |
| Cl (meq/l) | 0.30 | 0.34 | 0.04 | 0.50 | 0.50 | 0.00 |
| SiC | 0.12 | 0.56 | 0.44 | 0.42 | 0.25 | -0.17 |
| SiD | 0.04 | 1.09 | 1.05 | 0.65 | 0.60 | -0.05 |
| SiG | -2.10 | -1.33 | 0.77 | -1.74 | -0.53 | 1.21 |

Figure 15 Plots of mean solute compositions and selected SI's of roof drip and floor waters, and changes in these parameters due to chemical reactions in the mine. Data are representative of the April 1993 sampling period.

A) Change in floor water chemistry.



B) SI evolution of Longwall Area 3.

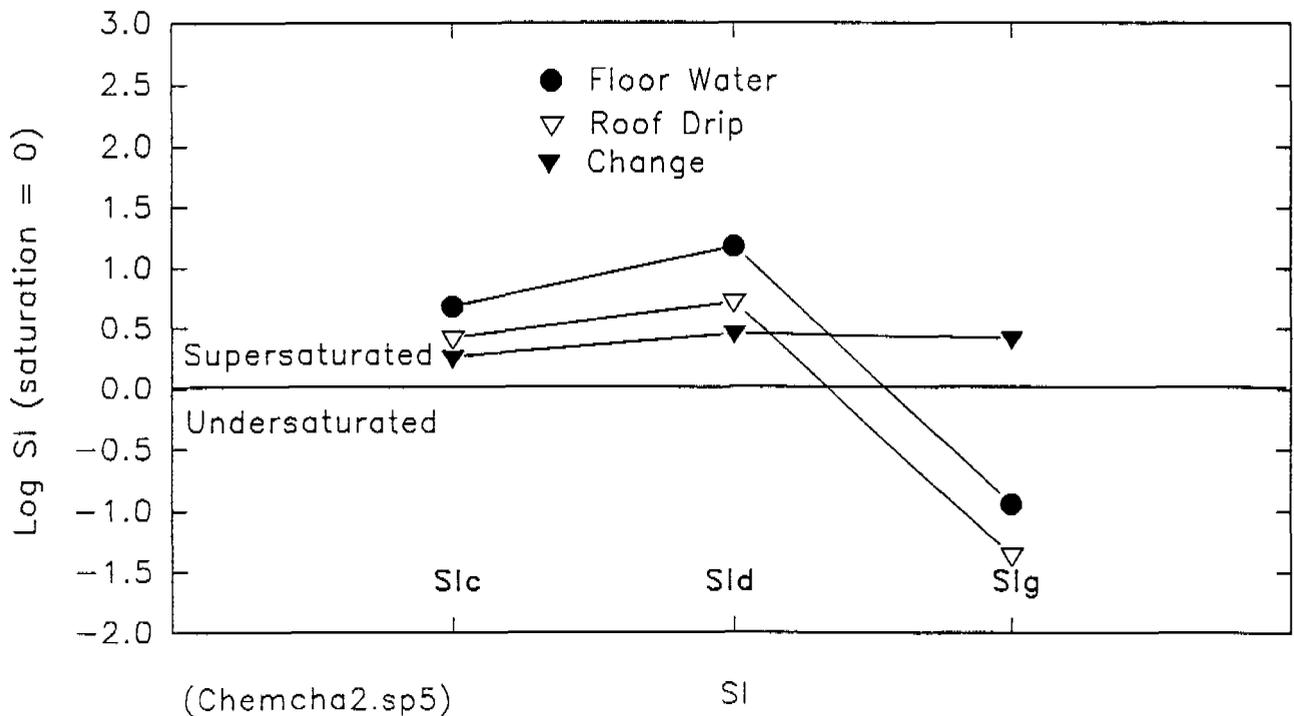
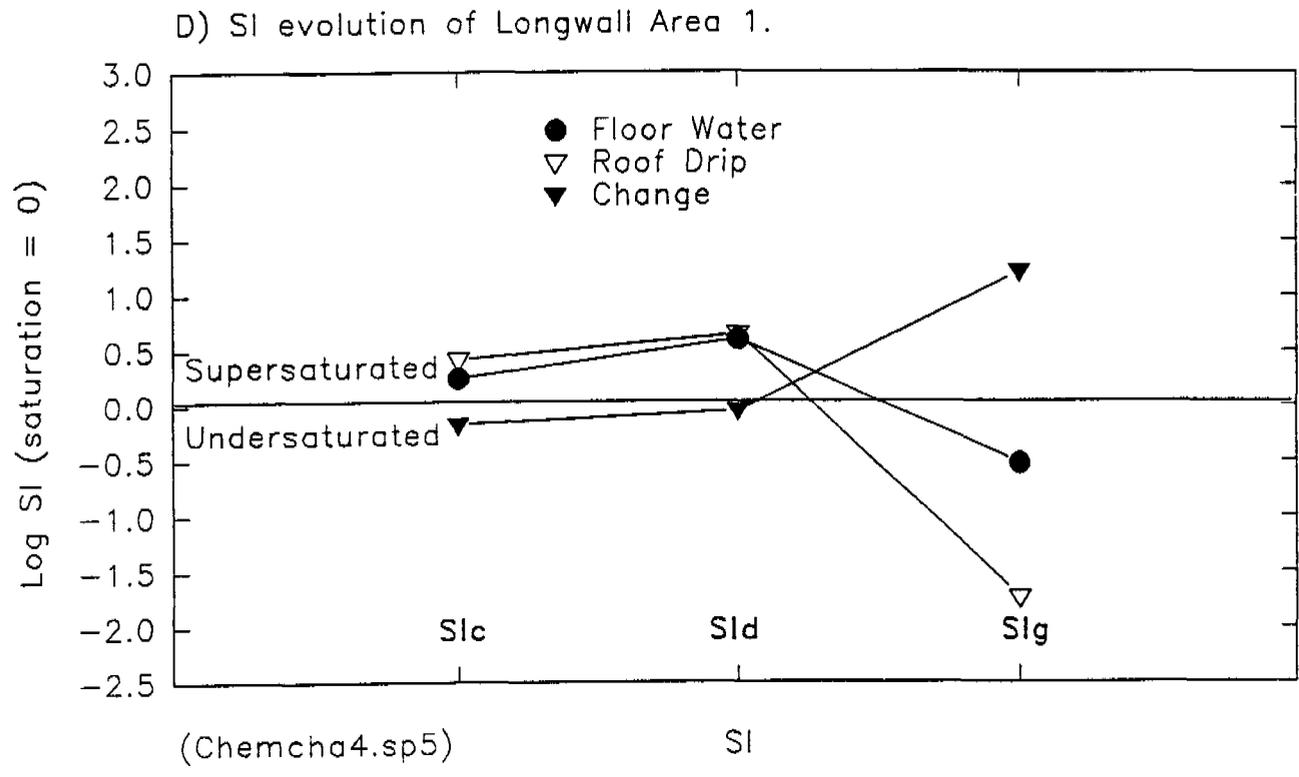
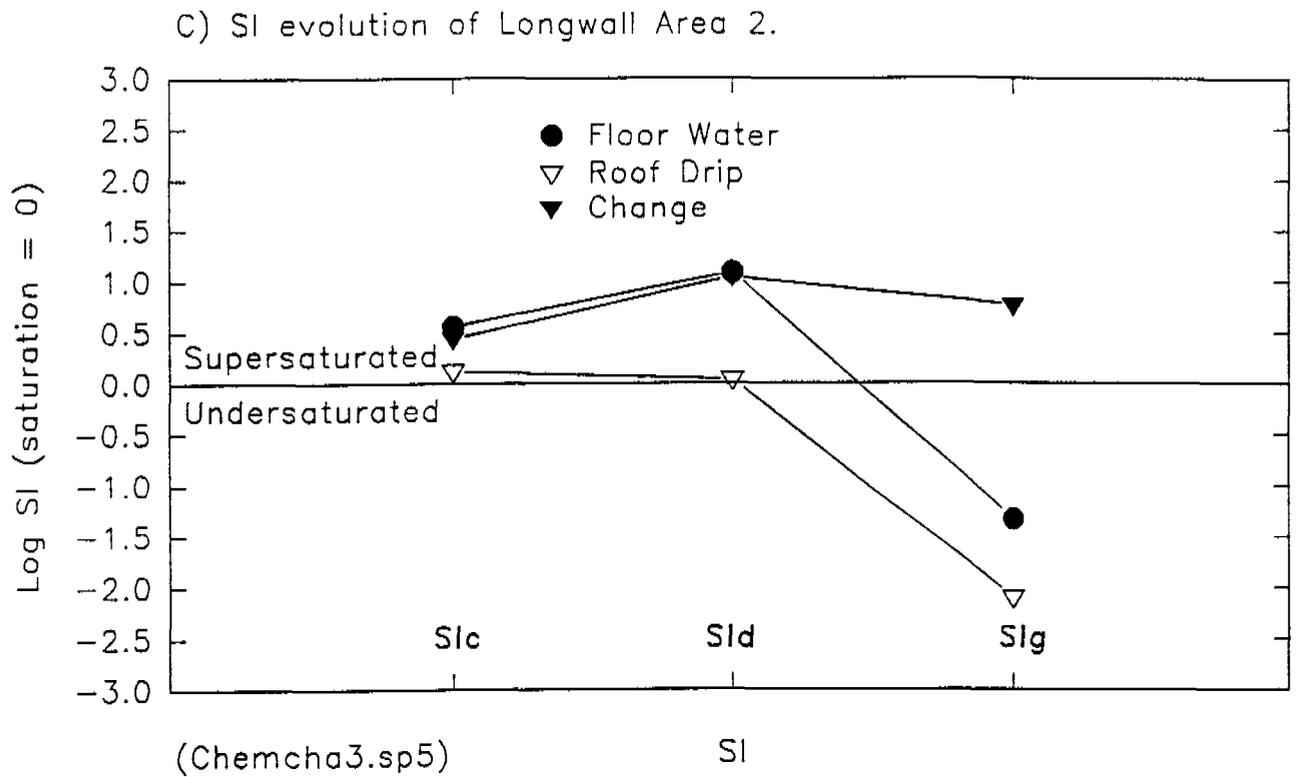


Figure 15 con't



The chemical evolutionary pathways of floor waters in each mining area differ somewhat, with Longwall Area 1 experiencing the greatest change. Except for a decrease in the HCO_3^{2-} content in Longwall Area 3, all significant concentration changes are positive.

Four factors appear to contribute to the observed changes:

- 1) precipitation of carbonate minerals from the supersaturated roof drip waters,
- 2) bacterial oxidation of the organic content of the leaked emulsion used as hydraulic fluid in the longwall mining operation,
- 3) dissolution of carbonate rocks used to fill low spots in the mine, and
- 4) dissolution of gypsum rock dust that covers exposed mine surfaces.

The computer code Balance (Parkhurst and others, 1982) was used to calculate the mass transfer of potential chemical reactions in each of the longwall areas (Table 6). Positive numbers indicate dissolution, and negative numbers indicate precipitation or outgassing. Units are millimoles per liter (mmole l^{-1}). Mass transfer was calculated for two conditions. Condition 1 assumed that the emulsion leaked from the longwall mining operation does not contribute to the overall chemistry of the floor water, whereas

Table 6 Calculated precipitation and dissolution of calcite, dolomite, gypsum and CO₂(g) in mine floor waters due to chemical reactions between roof drip waters and substances in the mine.

| | ----- Phase Change ----- (mmole/l) | | | |
|--------------|---------------------------------------|----------|---------|--------|
| | Calcite | Dolomite | CO2 Gas | Gypsum |
| Area 3 | | | | |
| W/o Emulsion | -1.750 | 0.245 | 0.090 | 2.225 |
| W/ Emulsion | -1.380 | 0.177 | -0.651 | 1.836 |
| Area 2 | | | | |
| W/o Emulsion | -2.005 | 0.975 | 2.815 | 1.690 |
| W/ Emulsion | -0.974 | 0.780 | 1.448 | 0.642 |
| Area 1 | | | | |
| W/o Emulsion | -10.965 | 4.905 | 8.445 | 9.560 |
| W/ Emulsion | -9.863 | 4.441 | 5.369 | 8.361 |

 negative phase change = precipitation
 positive phase change = dissolution

condition 2 assumed it did. Calculations of emulsion contributions were based on the idea that all excess Na^+ in the floor water was contributed from the emulsion. Appropriate percentage contributions of other ions from the emulsion were then calculated on the basis of the excess Na^+ in each mining area. Different percentage contributions were assigned to each longwall area, because the excess Na^+ content varied from one area to another.

Results of the mass transfer calculations are not consistent with purely inorganic reactions. The calculations indicate that dissolution of gypsum dust results in calcite precipitation and dolomite dissolution. Such reactions are thermodynamically plausible, considering the gypsum dust and the dolomite used in the mine. However, calculations of saturation indices indicate that floor waters in Longwall Areas 3 and 2 become more calcite supersaturated than the incoming roof drip waters. The condition of supersaturation is not unusual and is the result of kinetic factors. Mineral precipitation is often kinetically impaired; the energy required to initiate nucleation is greater than the thermodynamic energy needed to continue nucleation.

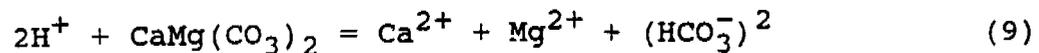
The calculations and the elevated HCO_3^{2-} content (Table 5) indicate that the floor waters in Longwall Areas 2 and 1 have acquired appreciable quantities of additional $\text{CO}_2(\text{g})$. Plausible

inorganic reactions in the mine, such as the decomposition of wood used as mine supports, are not capable of supplying extra $\text{CO}_2(\text{g})$ at the necessary rate, and an external source is needed. Additional $\text{CO}_2(\text{g})$ is needed to drive the dolomite dissolution reaction in Longwall Area 1. Sulfate reduction can liberate $\text{CO}_2(\text{g})$, but the mine is an oxidizing environment, and no $\text{HS}^-(\text{g})$ has been noted. Bacterial oxidization of organic matter in the emulsion leaked from the longwall mining machine is the likely source of the extra $\text{CO}_2(\text{g})$. The likely chemical reactions that contribute to the increase in the solute content of the floor waters are described below:

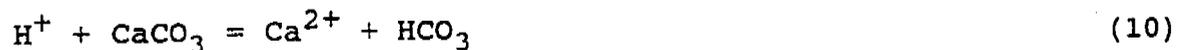
Gypsum dissolution



Dolomite Dissolution

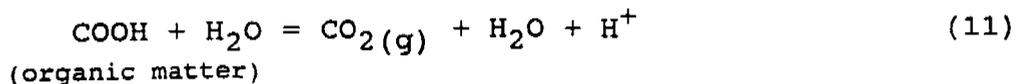


Calcite Dissolution and Precipitation

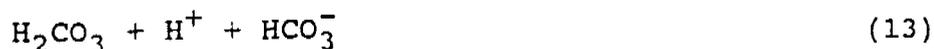


Acquisition of $\text{CO}_2(\text{g})$

Oxidation of Organic Matter



Formation and Dissociation of Carbonic Acid



The two key reactions are the dissolution of gypsum and the oxidation of residual emulsion in the older longwall areas. The dissolution of gypsum, which does not require free H^+ ions, increases the TDS by liberating both Ca^{2+} and SO_4^{2-} . Gypsum is very soluble and can greatly elevate the TDS. Elevated TDS's can cause the activity coefficients of all ionic species to decrease, thus permitting potential dissolution of additional carbonate minerals. Because Ca^{2+} is an ion common to gypsum and calcite, the dissolution of the more soluble gypsum causes precipitation of the less soluble calcite. The common ion effect does not influence dolomite in the same way because gypsum does not contain Mg^{2+} .

Increases in Ca^{2+} and Mg^{2+} from the dissolution of carbonate minerals requires the introduction of free H^+ ions. In the mine, the dissociation of carbonic acid (H_2CO_3) formed from $\text{CO}_2(\text{g})$ that has been liberated by the oxidation of the residual emulsion provides ample H^+ ions. This series of reactions, combined with the dissolution of residual gypsum, appears to be most active in Longwall Area 1, where the increase in solute content of all major ions is the greatest.

CONCLUSIONS

1. Nature of the Ground-Water System in the Upper Blackhawk Formation

Ground-water systems in the Upper Blackhawk Formation overlying the SUFCO mine are highly compartmentalized both horizontally and vertically. Variations in roof drip chemistry, the steady declines in roof drip rates after cessation of mining, and the variation in $\delta^{34}\text{S}$ in roof drip waters demonstrates that there are limited horizontal hydraulic connections between the various regions of the Upper Blackhawk Formation.

The age of the ground water, the perched water zones identified by the U.S. Geological Survey in the overlying aquifers, and the rapid decline in roof drip rates suggest that the Upper Blackhawk Formation has a poor hydraulic connection with potential recharge areas, the land surface, and overlying aquifers.

The horizontal and vertical compartmentalization of the ground-water systems above the Hiawatha Coal seam suggest that mining will rapidly dewater the ground-water system lo-

cated just above the coal seam but will have a limited effect on ground-water systems above and beyond that layer.

2. Causes of Mine Discharge Elevated TDS

The chemistry of the roof water leaking into the mine varies greatly between longwall areas. The TDS increases toward the eastern and northeastern portions of the mine and is greatest in the current mining area. However, the elevated TDS from roof drips in the current mining area is not the sole cause of the excessive TDS in the mine discharge water.

The 10-year hydrograph of mine water TDS indicates that the TDS has been steadily increasing during this time. This long-term increase is the result of three factors:

- a. dissolution of gypsum rock dust used as a fire and explosion retardant,
- b. bacterial oxidation of leaked longwall mining operation emulsion in the older longwall areas, and
- c. dissolution of carbonate crushed rock used to fill low regions in the mine floor.

Dissolution of gypsum dust is the principal factor in the current longwall area, whereas oxidation of leaked longwall emulsion is a very important factor in the older longwall areas. Although the discharge from the oldest longwall area is relatively small, this area contributes a disproportionate share of TDS.

3. Possible Future Trends in Mine TDS and Discharge Rates

Assuming that mining proceeds at a nearly constant rate and that unusual hydrogeologic conditions are not encountered in the mine, the maximum discharge rate from the mine will be about 1,000 to 1,100 gpm. The discharge rate will decline as the active mining area is mined out and will increase as new mining areas are developed.

Sealed mining areas will continue to contribute TDS to the mine discharge water. The TDS content of floor waters from sealed mining areas will not decline, but the mass contribution of TDS will decline because of reduced discharge rates. The effects of gypsum rock dust and leaked emulsion will not be appreciably lessened in the closed areas, because the collapse of gypsum rock dusted roof and wall areas will continue to bring gypsum into contact with mine floor water.

The recent substitution of calcite/dolomite rock dust for gypsum dust will reduce the TDS of mine discharge water. This reduction will result from the dilution of higher TDS floor water from the gypsum rock dusted portions of the mine with lower TDS floor water from calcite/dolomite rock dusted portions of the mine.

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APPENDIX A

REPORT ON CATION-ANION BALANCES
PREPARED BY MAYO AND ASSOCIATES
May 17, 1993

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May 17, 1993

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RE: Completion of Task 1 - Resolution of cation-anion balance
problem

Background

This report contains a summary of the activities that Mayo and Associates undertook between March and April 1993 to resolve the cation-anion balance error problem in the water quality analysis performed by Mountain States Analytical.

In late 1992 SUFCO personnel collected approximately 50 water and other fluid samples from the mine. The samples were collected in an attempt to understand the causes of elevated TDS in the mine discharge water. The samples were analyzed by Mountain States Analytical Laboratory in Salt Lake City, Utah. Most cation-anion

balance errors reported by Mountain States Analytical Laboratory exceeded the commonly accepted 5% error criteria, and balance errors as great 37.22% were reported. Balance errors do not affect TDS determinations. Balance errors are calculated as follows:

$$\text{error \%} = \frac{\Sigma \text{ cations} - \Sigma \text{ anions}}{\Sigma \text{ cations} + \text{ anions}} \times 100$$

Because it is not possible to perform accurate quantitative analysis of water quality data having such large balance errors, it was necessary to resolve the cation-anion balance error problem before we could begin to answer the larger questions: 1) what has been responsible for the increased TDS levels in the discharge water? and 2) what is the best way to resolve the TDS problem?

Analysis of the Problem and Conclusion

Possible causes of the cation-anion imbalance included problems in sampling, sample preservation, sample holding, laboratory analytical methods, or some combination of these problems. After discussing the potential problems with personnel of SUFCO and Mountain States Analytical and reviewing the available data, we designed and undertook a test field sampling and laboratory analytical program. The sampling plan was executed on February 2, 1993. The sampling and analytical plan was as follows:

1. Samples were collected from 3 different locations in the mine. Sampling locations were selected to represent the anticipated range of water chemistries occurring in the mine. The locations chosen were Rebuild Station, #4 Sump, and 3 West C 44.

2. At each site four sets of samples were collected for cation and anion analysis. Two sample sets were preserved using the standard SUFCO-Mountain States Analytical procedures. These standard procedures included 1) field acidification of cation samples without field filtration (i.e., 0.45 micron), and 2) laboratory titration for bicarbonate. The other two sample sets were preserved by field filtration of cation samples prior to acidification and field titration of bicarbonate. All samples were preserved by placed in coolers and immediately delivered to the laboratories for analysis.

Two sample sets, one utilizing each of the two field preservation techniques, were analyzed by Mountain States Analytical; and two identical sample sets were analyzed by Mayo and Associates. Results were compared between preservation techniques and between laboratories.

A third set of identical samples was sent to Ford Laboratory in order to obtain an independent check of the other laboratory results. Ford Laboratory was dropped from latter sampling rounds because they had similar high balance errors (5 to 8%) and their turn around time was too slow.

Laboratory results were disappointing. The field filtered cation results gave a slightly better cation-anion balance; however, all laboratory results had balance errors of less than 5%. Based on these laboratory results, which were completed on February 10, 1993, we concluded that the Mountain States Analytical had a laboratory problem that had subsequently been corrected.

On March 3, 1993, Mountain States Analytical reported water quality results for a routine sampling of mine discharge water. A balance error of 14.38 % was reported. Obviously the balance error problem had not been resolved by Mountain States Analytical.

Because the test program strongly suggested that field sampling and preservation techniques were not the problem, we focused our attention on the analytical procedures used by Mountain States Analytical. Mountain States Analytical uses an ICP for metal analysis. Their results were generally consistent with the AA results of Mayo and Associates and were considered a less likely source of error than the anion analysis. Mountain States Analytical uses wet chemical methods (titration) for bicarbonate and chloride, and a turbidimetric meter for sulfate. Chloride was ruled out as the probable cause because chloride concentrations are low in most samples and because Mountain States Analytical obtained results similar to those of Mayo and Associates, which uses a "state of the art" IC.

The two major anions in SUFCO waters are bicarbonate and sulfate. Mountain States Analytical routinely reported bicarbonate concentrations about 20% less than results of Mayo and Associates using similar titration methods. Mayo and Associates checked Mountain States' titration acid and standard solution against their own acid and standard solution and obtained similar results. It was found that Mountain States Analytical had been reporting total alkalinity (CaCO_3) as bicarbonate. The 20% error was due to Mountain States Analytical reporting CaCO_3 as HCO_3^- . This failure to report alkalinity properly did not ultimately affect the cation-anion balance error, because Mountain States Analytical did do the conversion before calculating the balance error.

After bicarbonate was ruled out, sulfate remained the likely candidate for the cation-anion imbalance. Turbidity meters are a very old technology and often have difficulty with elevated levels of sulfate and in those cases where other interferences occur.

It is our opinion that most of the balance error problems were due to sulfate analysis using the turbidity meter. We believe that with very careful work using appropriate dilutions, Mountain

States Analytical can achieve acceptable balance errors. In mid-April 1993, Mayo and Associates and SUFCO personnel executed an extensive water quality sampling program. Mountain States Analytical performed the laboratory analysis of the samples and had acceptable balance errors.

Sincerely,

Alan L. Mayo